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Preliminary Bounds on the Expected Postclosure Performance of the Yucca Mountain Repository Site, Southern Nevada

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PRELIMINARY BOUNDS ON THE EXPECTED POSTCLOSURE PERFORMANCE OF THE YUCCA MOUNTAIN REPOSITORY SITE, SOUTHERN NEVADA

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Abstract

Current data and understanding about the site conditions at Yucca Mountain provide a basis for calculating the likely range of performance of a mined repository for spent nuclear fuel. Low flux through the unsaturated zone results in groundwater travel times to the water table that probably exceed 10,000 years and may exceed 100,000 years, far longer than required by the NRC. The low flux will also limit releases of waste from the waste packages, probably to annual amounts less than one millionth of the mass of the waste inventory remaining 1000 years after repository closure; the corresponding releases of curies would be well within the allowable releases set by the NRC. Geochemical retardation by sorption and diffusion will slow radionuclide movement relative to groundwater flow by factors of hundreds to thousands for many waste species. In combination, these site conditions provide a high degree of confidence that no releases to the accessible environment will occur during the first 10,000 years after repository closure, the time period for which the EPA has set release limits. Carbon-14, technetium-99, iodine-129, and various nuclides of uranium sorb poorly on the tuffs along the flow paths and, together with uranium daughter products, will be the first radionuclides to arrive at the water table. The total radioactivity produced by these and later arriving contaminants will remain far below the allowable releases, even for periods of millions of years, if expected flux conditions prevail. If the flux is currently greater than the values inferred from the measured in situ moisture contents of the volcanic rocks or if it were to increase in the future, fracture flow and attendant short flow times to the water table could occur. Even if rapid fracture flow were to occur, release of wastes to the accessible environment would probably remain low with respect to the EPA's limits, because diffusion of radionuclides from the fractures into the rock matrix would ensure slow migration of most of the wastes through the sorbing matrix.

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PRELIMINARY BOUNDS ON THE EXPECTED POSTCLOSURE PERFORMANCE OF THE YUCCA MOUNTAIN REPOSITORY SITE, SOUTHERN NEVADA

CHAPTER 1. INTRODUCTION

1.1 PURPOSE

This report summarizes some current conclusions about the expected performance of a potential repository site at Yucca Mountain in southern Nevada (Figure 1). In particular, the capabilities of the current geologic and hydrologic environments to isolate radioactive wastes placed in a repository located in the unsaturated, densely welded tuffs of the Topopah Spring Member of the Paintbrush Tuff (Figure 2) are addressed in terms of certain regulatory requirements. These requirements are set forth by (1) the Department of Energy (DOE) as "General Guidelines for Recommendation of Sites for Nuclear Waste Repositories" in a November 13, 1983, draft of 10 CFR Part 960 (DOE, 1983); (2) the Nuclear Regulatory Commission (NRC) as "Technical Criteria for Disposal of High-Level Radioactive Wastes in Geologic Repositories" published as a final rule in 10 CFR Part 60 (NRC, 1983); and (3) by the Environmental Protection Agency (EPA) in "Environmental Standards for the Management and Disposal of Spent Nuclear Fuel, High-Level and Transuranic Wastes," a proposed rule in 40 CFR Part 191 (EPA, 1982; 1984).

The report was prepared for the Nevada Nuclear Waste Storage Investigations (NNWSI) Project, which is administered from the DOE's field office in Las Vegas, Nevada. Data to support our conclusions are abstracted from a number of formal and informal reports generated by technical participants in the NNWSI Project, as well as from a few simple calculations that appear in the following sections. The technical participants who supplied data for this report are primarily from the U.S. Geological Survey, Sandia National Laboratories, Lawrence Livermore National Laboratory, and Los Alamos National Laboratory. However, the interpretations or uses of data that appear in this report are those of the authors.

This report is intended, in part, to provide some of the information required to support an environmental assessment document. If Yucca Mountain is selected by the DOE as one of at least five sites to be nominated as suitable for site characterization, the environmental assessment will be prepared to support that nomination in accordance with the DOE siting guidelines (DOE, 1983) and the Nuclear Waste Policy Act of 1982 (U.S. Congress, 1983). The analyses in this report rely on assumptions about the engineered and site features of a repository that may differ from those eventually used in the environmental assessment. Nonetheless, our conclusions are offered for use by the DOE in its efforts to prepare the environmental assessment, should Yucca Mountain be nominated, or for use in its decision not to nominate Yucca Mountain, should that be the chosen course. However, our broader objective is to organize the current understanding of the natural features of Yucca Mountain in such a way that the reader can begin to form opinions about the suitability of a site at Yucca Mountain for isolating nuclear wastes in an underground repository.

1.2 APPLICABLE REGULATORY REQUIREMENTS

Only two regulatory requirements are directly amenable to evaluation in the sole context of natural conditions at Yucca Mountain, and both requirements address the same condition. They are

1. A 1,000-yr pre-waste-emplacement groundwater flow time from the disturbed zone to the accessible environment, an NRC performance objective for the geologic setting of nuclear waste repositories, 10 CFR 60.113(2) (NRC, 1983).
2. A similar requirement for a 1,000-yr flow time from the disturbed zone to the accessible environment, a proposed disqualifying condition of the DOE listed in its technical guideline for geohydrology, 10 CFR 960.4.2.1(d) (DOE, 1983).

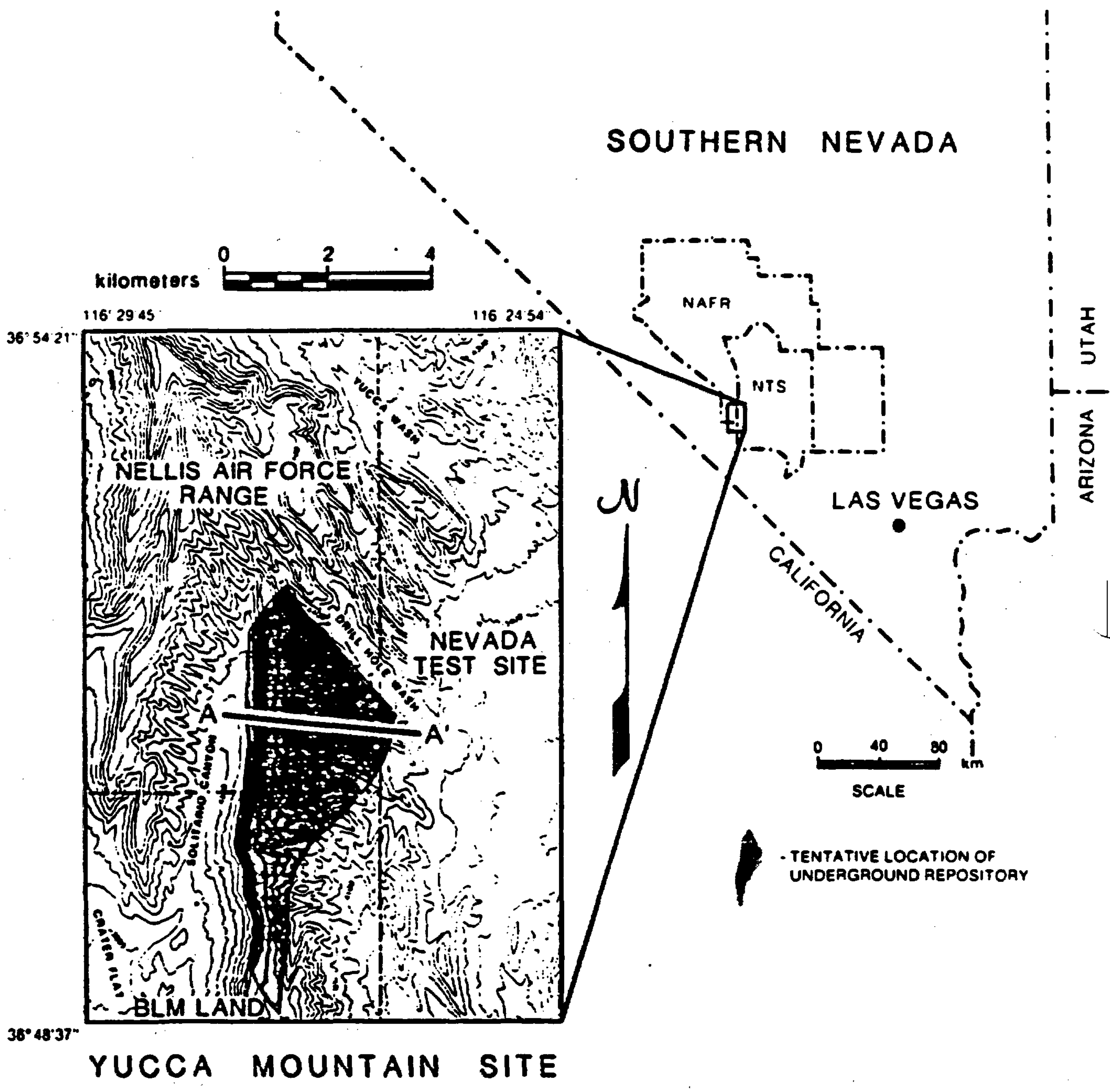


Figure 1. Location of the site for a possible radioactive-waste repository at Yucca Mountain in southern Nevada; A-A' shows the location of the geologic cross section in Figure 2.

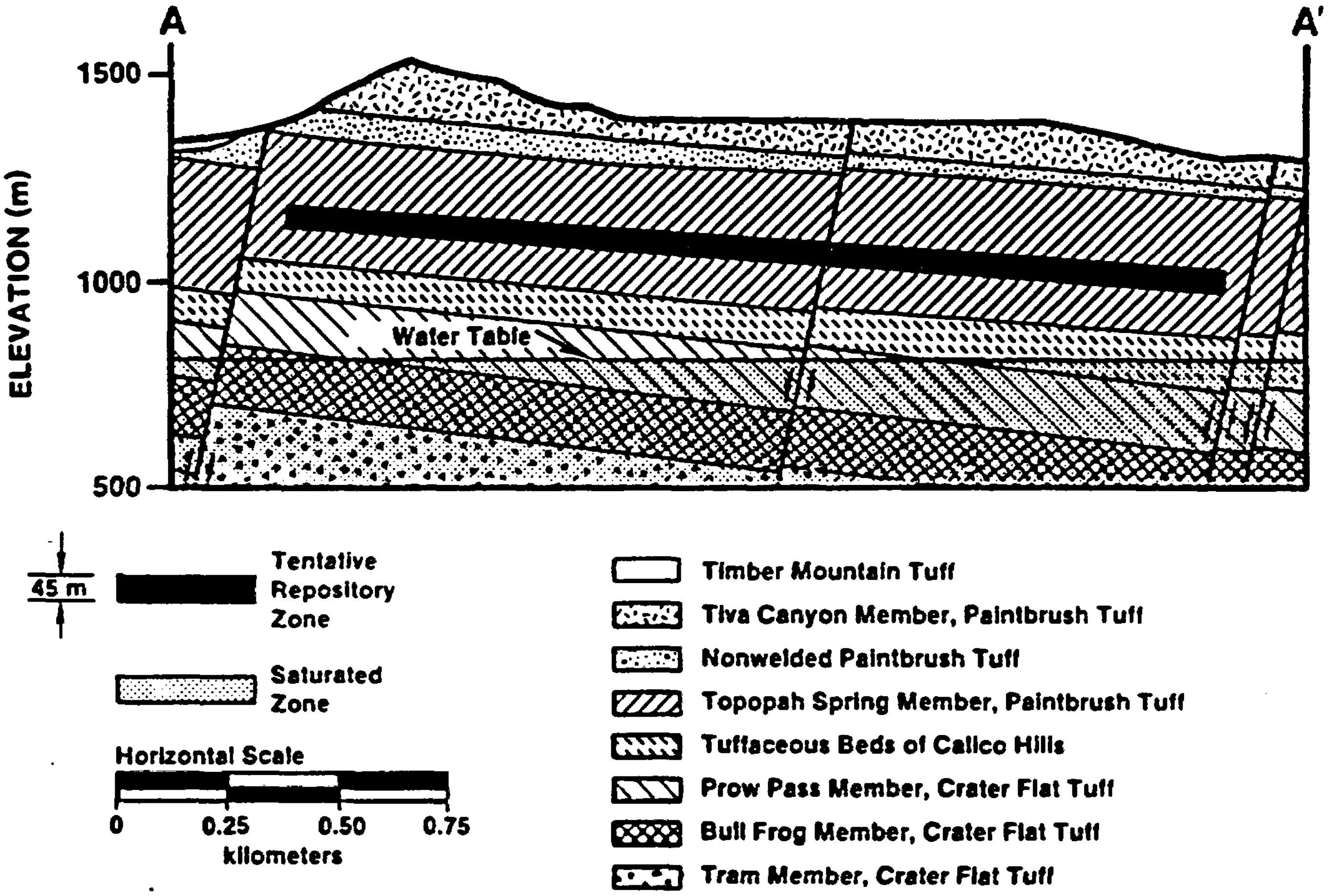


Figure 2. Geologic cross section of Yucca Mountain showing the tentative depth of a possible repository in the Topopah Spring Member of the Paintbrush Tuff.

The 1000-yr flow-time requirement of the NRC is not rigid, in the sense that mitigating circumstances that would permit compliance with radiological standards may be sufficient to allow the agency to waive the flow-time prescription.

Other regulatory requirements must be evaluated in the context of both natural conditions at a site and engineered components of a repository constructed at that site. The contribution of natural conditions to satisfying these requirements can be assessed only under certain assumptions about the engineered system. In this spirit, we will make the necessary assumptions explicit in order to evaluate the expected performance of the Yucca Mountain site with respect to the following regulations:

1. The annual release rate of any radionuclide from the engineered barrier system after closure of the repository shall not exceed 1 part in 100,000 of the total amount of that radionuclide calculated to be present 1,000 yr after permanent closure. This is an NRC performance objective for the engineered system. These release limits are shown in Table 1. Any radionuclide constituting less than 0.1% of the total release limit is exempt from this requirement, 10 CFR 60.113(a,1,ii,B) (NRC, 1983).
2. Reasonably foreseeable releases of radionuclides to the accessible environment shall be less than the quantities calculated according to procedures specified in Table II of 40 CFR 191. This is a proposed EPA containment requirement, 40 CFR 191.13(a) (EPA, 1982; 1984). These limits are shown in the last column of Table 1.
3. Releases of radioactive material to the accessible environment shall conform with generally applicable environmental standards established by the EPA. This is an overall system performance objective of the NRC, 10 CFR 60.112

Table 1. Radionuclide inventory of spent fuel and allowable release of the NRC and EPA.

Isotope	Half Life (yr)	Specific Activity (Ci/g)	Inventory (Ci/1000 MTHM) t = 10 yr[(a)]	t = 360 yr[(b)]	t = 1060 yr[(b)]	Annual NRC Release Limits From Repository (Ci/1000 MTHM.)[(c)]	EPA Cumulative Release Limits at Accessible Environment (Ci/1000 MTHM)[e]
^{246}Cm	5.5×10^{3}	2.64×10^{-1}	3.5×10^{1}	3.4×10^{1}	3.1×10^{1}	3.1×10^{-4} (NA)[(d)]	100
^{245}Cm	9.3×10^{3}	1.57×10^{-1}	1.8×10^{2}	1.8×10^{2}	1.7×10^{2}	1.7×10^{-3} (NA)	100
^{244}Cm	1.76×10^{1}	8.32×10^{1}	9.0×10^{5}	9.3×10^{-1}	0	0 (NA)	100
^{242}Cm	4.5×10^{-1}	3.32×10^{3}	8.5×10^{3}	3.5×10^{1}	3.2×10^{1}	3.2×10^{-4} (NA)	100
^{243}Am	7.95×10^{3}	1.85×10^{-1}	1.4×10^{4}	1.4×10^{4}	1.3×10^{4}	1.3×10^{-1}	100
^{242}Am	1.52×10^{2}	9.72	1.0×10^{4}	3.4×10^{3}	3.1×10^{1}	3.1×10^{-4} (NA)	1000
^{241}Am	4.58×10^{2}	3.24	1.6×10^{6}	1.8×10^{3}	1.7×10^{2}	1.7×10^{-3} (NA)	100
^{242}Pu	3.79×10^{5}	3.90×10^{-3}	1.6×10^{3}	1.6×10^{3}	1.6×10^{3}	1.6×10^{-2}	100
^{241}Pu	1.32×10^{1}	1.12×10^{2}	6.9×10^{7}	1.8×10^{2}	1.7×10^{2}	1.7×10^{-3} (NA)	100
^{240}Pu	6.58×10^{3}	2.26×10^{-1}	4.5×10^{5}	4.4×10^{5}	4.1×10^{5}	4.1	100
^{239}Pu	2.44×10^{4}	6.13×10^{-2}	2.9×10^{5}	2.9×10^{5}	2.8×10^{5}	2.8	100
^{238}Pu	8.6×10^{1}	1.75×10^{1}	2.0×10^{6}	1.6×10^{5}	3.2×10^{1}	3.2×10^{-4} (NA)	100
^{239}Np	6.4×10^{-3}	2.33×10^{5}	1.4×10^{4}	1.4×10^{4}	1.3×10^{4}	1.3×10^{-1}	1000
^{237}Np	2.14×10^{6}	7.05×10^{-4}	3.1×10^{2}	2.7×10^{2}	2.7×10^{2}	2.7×10^{-3} (NA)	100
^{238}U	4.51×10^{9}	3.33×10^{-7}	3.2×10^{2}	3.2×10^{2}	3.2×10^{2}	3.2×10^{-3} (NA)	100
^{236}U	2.39×10^{7}	6.34×10^{-5}	2.2×10^{2}	2.2×10^{2}	2.3×10^{2}	2.3×10^{-3} (NA)	100
^{235}U	7.1×10^{8}	2.14×10^{-6}	1.6×10^{1}	1.6×10^{1}	1.6×10^{1}	1.6×10^{-4} (NA)	100
^{234}U	2.47×10^{5}	6.18×10^{-3}	7.4×10^{1}	7.4×10^{1}	7.5×10^{1}	7.5×10^{-4} (NA)	100
^{233}U	1.62×10^{5}	9.47×10^{-3}	3.8×10^{-2}	4.5×10^{-1}	1.3	1.3×10^{-5} (NA)	100
^{231}Pa	3.25×10^{4}	4.51×10^{-2}	5.3×10^{-3}	1.3×10^{-1}	3.7×10^{-1}	3.7×10^{-6} (NA)	100
^{232}Th	1.4×10^{10}	1.10×10^{-7}	1.1×10^{-7}	4.1×10^{-6}	1.2×10^{-5}	1.2×10^{-10} (NA)	100
^{230}Th	8.0×10^{4}	1.94×10^{-2}	4.1×10^{-3}	2.2×10^{-1}	6.6×10^{-1}	6.6×10^{-6} (NA)	100
^{229}Th	7.34×10^{3}	2.13×10^{-1}	2.8×10^{-5}	8.3×10^{-4}	6.6×10^{-3}	6.6×10^{-8} (NA)	100
^{226}Ra	1.60×10^{3}	9.88×10^{-1}	7.4×10^{-6}	2.3×10^{-1}	6.7×10^{-1}	6.7×10^{-6} (NA)	100
^{225}Ra	4.05×10^{-2}	3.92×10^{4}	8.1×10^{-5}	8.4×10^{-4}	6.7×10^{-3}	6.7×10^{-8} (NA)	100
^{210}Pb	2.23×10^{1}	7.63×10^{1}	7.0×10^{-7}	2.4×10^{-1}	7.2×10^{-1}	7.2×10^{-6} (NA)	1000
^{137}Cs	3.0×10^{1}	8.70×10^{1}	7.5×10^{7}	2.3×10^{4}	2.2×10^{-3}	2.2×10^{-8} (NA)	1000
^{135}Cs	3.0×10^{6}	8.82×10^{-4}	2.7×10^{2}	2.7×10^{2}	2.7×10^{2}	2.7×10^{-3} (NA)	1000
^{129}I	1.59×10^{7}	1.74×10^{-4}	3.3×10^{1}	3.3×10^{1}	3.3×10^{1}	3.3×10^{-4} (NA)	1000
^{126}Sn	1.0×10^{5}	2.84×10^{-2}	4.8×10^{2}	4.8×10^{2}	4.8×10^{2}	4.8×10^{-3} (NA)	1000
^{99}Tc	2.15×10^{5}	1.70×10^{-2}	1.3×10^{4}	1.3×10^{4}	1.3×10^{4}	1.3×10^{-1}	10,000
^{93}Zr	9.5×10^{5}	4.04×10^{-3}	1.7×10^{3}	1.7×10^{3}	1.7×10^{3}	1.7×10^{-2}	1000
^{90}Sr	2.9×10^{1}	1.37×10^{2}	5.2×10^{7}	1.2×10^{4}	6.5×10^{-4}	6.5×10^{-9} (NA)	1000
^{59}Ni	8.0×10^{4}	7.57×10^{-2}	3.0×10^{1}	3.0×10^{1}	3.0×10^{1}	3.0×10^{-4} (NA)	1000
^{14}C	5.73×10^{3}	4.45	1.4×10^{2}	1.3×10^{2}	1.2×10^{2}	1.2×10^{-3} (NA)	100
						$\Sigma = 7.3 \times 10^{0}$	

(a) 10 years out of the reactor, i.e., the assumed time of emplacement, values from DOE, 1979.
(b) 300 or 1000 years after closure, i.e., 360 or 1060 years out of reactor, assuming a 50-year operations period before closure; values calculated from (a) and rounded to 2 significant digits.
(c) 1×10^{-5} times inventory at 1060 years; from NRC (1983)
(d) NA means not applicable because curies remaining at 1060 years are less than about 7.3×10^{-3} Ci, i.e., less than 0.1% of the total release rate limit of about 7.3 Ci/yr; each of these nuclides thus has a release rate limit of 7.3×10^{-3} Ci/yr.
(e) Applied 10,000 years after repository closure; from EPA (1984).

(NRC, 1983), taken in this report to be the same as the above-listed 40 CFR 191.13(a).

4. Radioactive wastes shall be physically separated from the accessible environment in accordance with the requirements set forth in 10 CFR 60 and 40 CFR 191. This is a DOE system guideline, 10 CFR 960.4.1, taken in this report to be synonymous with the two previously listed requirements.

The three latter requirements, one by each federal agency responsible for regulating nuclear-waste disposal, are restatements of a single requirement, i.e., to comply with performance standards to be set by the EPA. The DOE guidelines for expected postclosure performance (10 CFR 960.4-2-1 through 960.4-2-3) contain three requirements addressing geohydrology, geochemistry, and rock characteristics, respectively. These guidelines restate the requirement to satisfy the postclosure system guideline, 10 CFR 960.4-1, and, by reference, the EPA and the NRC performance standards. Thus, the entire list of regulatory requirements for expected repository behavior addressed in this report reduces to only three topics: groundwater-flow time, a release rate from the engineered barrier system, and cumulative releases of radionuclides to the accessible environment.

Other parts of 10 CFR 60, 40 CFR 191, and 10 CFR 960 list numerous factors that must be considered in assessing expected performance of a repository, but these factors are not requirements. Still other parts of the regulations list requirements, as well as factors to consider, for assessing unexpectedly disrupted long-term conditions, preclosure performance, engineering features, or nonradiological concerns. Because this report is limited to discussion of natural conditions affecting expected long-term radiological performance, these latter concerns are beyond the scope of our intentions and are not addressed.

1.3 ORGANIZATION OF THE REPORT

Chapter 2, following this introduction chapter, lists several general assumptions used for our analyses. Chapter 3 summarizes current information about site properties in the context of the proposed DOE technical guidelines for expected postclosure performance. The three pertinent guidelines address geohydrology (Section 3.1), geochemistry (Section 3.2), and rock characteristics (Section 3.3). In Chapter 4, compliance with the applicable NRC and EPA requirements is discussed, drawing from the general site information presented in Chapter 3. It has three sections that separately address the NRC requirements for groundwater-flow time (Section 4.1), limited releases from the engineered barrier system (Section 4.2), and the EPA requirements for limited releases to the accessible environment (Section 4.3). Chapter 5 concludes the report with some observations about how well Yucca Mountain might be expected to comply with current regulations and about the remaining uncertainties that are the most important to resolve should site characterization of Yucca Mountain be undertaken.

CHAPTER 2. GENERAL ASSUMPTIONS

Several assumptions are necessary for predicting the expected performance of any repository system. At this time, the site-specific features of the engineered repository have not been determined, nor has the nature of the waste or its exact form. In addition, certain properties and physical mechanisms that occur at Yucca Mountain, but have not been fully determined, must be postulated to allow meaningful analysis of site performance. The broad assumptions listed in this chapter address these topics from the perspective of how they will influence the actual behavior of a repository at Yucca Mountain and, consequently, its prediction. The assumptions are presented early in the report to provide a background for understanding the roles and limitations of the various site features discussed in Chapter 3, as they might influence site performance, discussed in Chapter 4. These assumptions are also made explicit to allow proper interpretation of the conclusions drawn in Chapter 5. The assumptions are

1. A repository will be located in the lower part of the Topopah Spring Member of the Paintbrush Tuff at Yucca Mountain, along the southwest edge of the Nevada Test Site (NTS) in southern Nevada (Figures 1 and 2). This assumption reflects the current preferred siting option of the DOE for a repository at or near the NTS and is supported by policy decisions based in part on reports detailing site-screening activities (Sinnock and Fernandez, 1982) and evaluations of alternative host rocks (Johnstone et al., 1984).
2. The repository will contain 70,000 metric tons of heavy metal (MTHM) in the form of about 35,000 canisters of spent fuel that will be 10 yr old (i.e., 10 yr after removal from its reactor core) when simultaneously emplaced in the repository. The inventory of waste assumed to be present at the time of emplacement is shown in Table 1.
3. The total area encompassing the waste will be 6.07×10^6 m^2 (about 1500 acres), yielding an initial thermal-power output of about 12-13 W/m^2 (about 50 kW/acre) (Jackson et al., eds., 1984), assuming that each 10-yr-old MTHM generates about 1.1 kW of thermal power (DOE, 1980).
4. No waste will dissolve or otherwise be removed from the emplacement location until the spent fuel is either 360 or 1060 yr old (or until approximately 300 or 1000 yr after closure of the repository*), at which times the thermal output of the waste will have decayed to about 0.15 or 0.05 kW/MTHM, equivalent to about 1.75 or 0.6 W/m^2 (7 or 2.3 kW/acre) (DOE, 1980). This assumption is based on the requirement by the NRC in 10 CFR 60.113 (a,1,ii,A) that containment within the engineered system must be essentially complete for at least 300 yr following closure and that complete containment may not be assumed for a greater period than 1000 yr. Thus, in order to build a repository (i.e., receive a license) complete containment for 300 to 1000 yr will be a fact of expected performance. The inventory of waste calculated to be present 300 and 1000 yr after closure of a repository is shown in Table 1.
5. All releases of waste from the repository will be caused by groundwater that flows through the repository and dissolves the spent fuel. The uranium-oxide matrix of the spent fuel will dissolve at a rate that allows the flowing water to become saturated with uranium. Other radionuclides in the spent fuel will dissolve congruently with uranium on a relative-mass basis. That is, at any given time, the ratio of the mass of uranium to the mass of any other radionuclide will be the same in the spent fuel as it is in the water that is dissolving the fuel.
6. The solubility of uranium will depend on the local geochemical conditions around the waste packages. The conditions around the waste when it begins to dissolve will be similar to those now occurring in the unsaturated zone at Yucca Mountain. This assumption rests in part on assumption 4, which indicated that heat from the repository will have decayed to low levels of output and, therefore, will not significantly affect repository behavior after the 300- or 1000-yr period of complete containment. Accordingly, the solubility of uranium is assumed to remain constant following the containment period.
7. The amount of water available to dissolve and transport waste in the unsaturated zone will be a fraction of the total water moving through the repository level. This fraction will depend on the

*360 and 1060 yr represent emplacement of 10-yr-old spent fu[el,] 50 yr of operations through a retrieval period, and 300 and 10[00] yr following closure at the end of the retrieval period.

amount of surface water that infiltrates the earth's surface, the amount of this infiltration that penetrates deeply enough to pass through the repository (i.e., the flux), the total area of the repository, the portion of this area occupied by the underground facilities, the spacing and location of waste canisters within the underground facilities, and the nature of unsaturated flow including the relationship of flow in the rock matrix and in fractures.

8. The flow path from the repository to the accessible environment will be vertically downward through the unsaturated zone to the water table, then horizontally along the water table for 2 or 10 km. These two ends of the flow path are assumed to be alternative boundaries of the accessible environment.
9. Water-flow velocity away from the repository will be equal to the flux divided by the effective porosity of the materials through which flow occurs.
10. The transport velocity of any radionuclide along flow paths away from the repository will be equal to be the water velocity divided by a total retardation factor for that radionuclide in the material through which the water flows. The retardation factor represents the combined effects of radionuclide sorption, mineral precipitation, and any other mechanism, such as diffusion, that will slow the net migration of waste species.
11. The decay of radionuclides in time and the resulting accumulation of daughter products are assumed to occur in a manner described by a system of equations, first developed by Bateman (1910), allowing five members of each decay chain to be considered. For the neptunium series Pu-241, Am-241, and Ra-225 are assumed to remain in secular equi-librium with their parent species. Similarly, for the uranium series Pu-238, Am-242, Cm-242, Pb-210, and Ra-226 are assumed to remain in secular equilibrium with their parent species. For the actinium series Np-239 is assumed to remain in secular equilibrium with its parent species. All fission products are treated as single-member chains. Table 1 shows the initial inventory assumed to be present in 10-yr-old spent fuel and the calculated inventories after the radionuclides have decayed for 360 and 1060 yr.

Given the general assumptions and boundary conditions listed above, it is not necessary to use sophisticated groundwater flow models or complex contaminant-transport equations to estimate radionuclide transport times and amounts at a repository site. On the contrary, the assumptions enable a simple, conservative investigation of the proper bounds to place on the expected performance of a repository at Yucca Mountain. In Chapter 4, the bounds are established under a range of values for several critical site conditions. Ancillary assumptions are necessary for determining the appropriate values or ranges of values for these site conditions, including groundwater flux, sorption coefficients, uranium solubility, and others. The basis for these latter assumptions will be made explicit in the following sections. Finally, specific assumptions are necessary to support the definitions of regulatory terms such as "disturbed zone," "engineered barrier system," "accessible environment," and others, as well as about the specific geometrical arrangement of repository facilities. These assumptions will be made at the appropriate places in Chapter 4 where they can be clearly tied to the calculations of performance.

A word of caution is in order. The conclusions in this report are based on current information about Yucca Mountain. Much of this information is preliminary. It is commonly limited in terms of either statistical reliability or understanding of the physical mechanisms that act through the site properties. Future investigations at Yucca Mountain or studies about nuclear-waste disposal in general may reveal flaws in the data, assumptions, or analysis techniques used in this report. To reduce the potential for misinterpretation or misrepresentation of site behavior, we have used and identified, wherever possible, conservative assumptions and analysis techniques, i.e., those that tend to err on the side of more deleterious predictions. We have also included calculations based on ranges of values for site properties wherever uncertainty is great or where the calculations are particularly sensitive to the assumed ranges in values. This paper should not be taken as a definitive analysis of the capability of the Yucca Mountain site to meet regulatory requirements. It should be interpreted only as a means to place the strengths and weaknesses of the site in proper perspective. In this spirit we hope this report will aid the making of impending decisions about whether an investment in extended site characterization is justified and, if characterization is begun, about the data that are most critical to gather for ensuring compliance with the applicable regulations for expected long-term repository performance.

CHAPTER 3. SITE CONDITIONS

This section outlines the known and assumed physical conditions relevant for assessing the expected postclosure performance of a repository at Yucca Mountain. It is divided into three subsections addressing, in order, geohydrology, geochemistry, and rock characteristics. These three topics correspond to the three proposed siting guidelines of the DOE for expected postclosure conditions and processes (DOE, 1983). Because the guidelines have not been published as a final rule, they are subject to change. For the version current at the time of this writing each guideline lists a qualifying condition and several favorable and potentially adverse conditions. In the guideline for geohydrology a disqualifying condition is also listed, as described in Section 1.2. We do not attempt to argue whether Yucca Mountain qualifies under each guideline, nor do we specifically discuss whether the site has any of the favorable or potentially adverse conditions corresponding to each guideline. Chapter 4, which addresses the NRC and EPA requirements, presents analyses that can be used to determine whether the site satisfies the intent of the guidelines for these three topics. This chapter uses the proposed siting guidelines solely as an organizing principle for discussing the data and associated assumptions about the physical conditions at Yucca Mountain, deferring to the following chapter the analyses needed to judge whether the site may be expected to comply with regulatory requirements.

3.1 GEOHYDROLOGY

The movement of water through a repository site is important for two basic reasons, it sets an upper limit on how much waste can be dissolved within a repository and how rapidly wastes can migrate in solution toward the accessible environment. The hydrologic conditions at Yucca Mountain needed for analyses of repository behavior are, therefore, those that will influence the dissolution of emplaced waste and the movement of waste with groundwater between the repository and the accessible environment. At Yucca Mountain these conditions are determined in large part by relationships between the hydrologic characteristics of the rocks along the flow paths and the amount of water moving through the mountain. To address these relationships, this section first outlines the general stratigraphic and structural features of the rocks at Yucca Mountain (Section 3.1.1), and then discusses the amount of water expected to move through the various rock units and structures (Section 3.1.2). Finally, these two topics are combined under the dictates of Darcy's law as extended to unsaturated flow to outline the manner in which the water flux will move through the Yucca Mountain environment (Section 3.1.3). Separate subsections address flow behavior in the unsaturated zone (Section 3.1.3.1) and the saturated zone (Section 3.1.3.2).

3.1.1 Stratigraphic and Structural Setting

The general hydrogeologic stratigraphy of Yucca Mountain and its relation to groundwater flow paths are shown in Figure 3. Six general hydrogeologic units are distinguished by their flow characteristics. They are, from top to bottom: the densely welded Tiva Canyon unit, the nonwelded Paintbrush unit, the densely welded Topopah Spring member, the nonwelded vitric Calico Hills unit, the nonwelded zeolitic Calico Hills unit, and the older tuff unit. Tables 2 and 3 summarize the hydrologic characteristics of these units.

The densely welded Tiva Canyon unit is the caprock at Yucca Mountain and is densely fractured (Table ~ Its matrix-saturated hydraulic conductivity is v… low, on the order of 1 mm/yr. Bulk porosity is about 10%. Effective matrix porosity is probably somewhat less, even under saturated conditions (Thordarson, 1983). This unit occurs entirely above the water table, and saturation is estimated as about 75% on the basis of laboratory measurements of core samples (Table 3).

The underlying nonwelded Paintbrush unit is less de…ely fractured and has a matrix-saturated hydraulic conductivity of several millimeters per year. Bulk porosity is very high, about 45%, and effective porosity is probably also high relative to the densely welded units. Saturation of this unit is apparently about 55% based on laboratory measurements of core samples (Table 3).

The tentative host rock for a repository at Yucca Mountain is the next lower unit, the densely welded Topopah Spring unit (Table 2). It is densely fractured and has a low matrix-saturated hydraulic conductivity, nearly identical to that of the densely welded Tiva Canyon unit. Bulk porosity is about 15%, and effective matrix porosity is assumed to be about 10%. Saturation, based on both field and laboratory measurements, appears to be about 70% (Table 3). I…

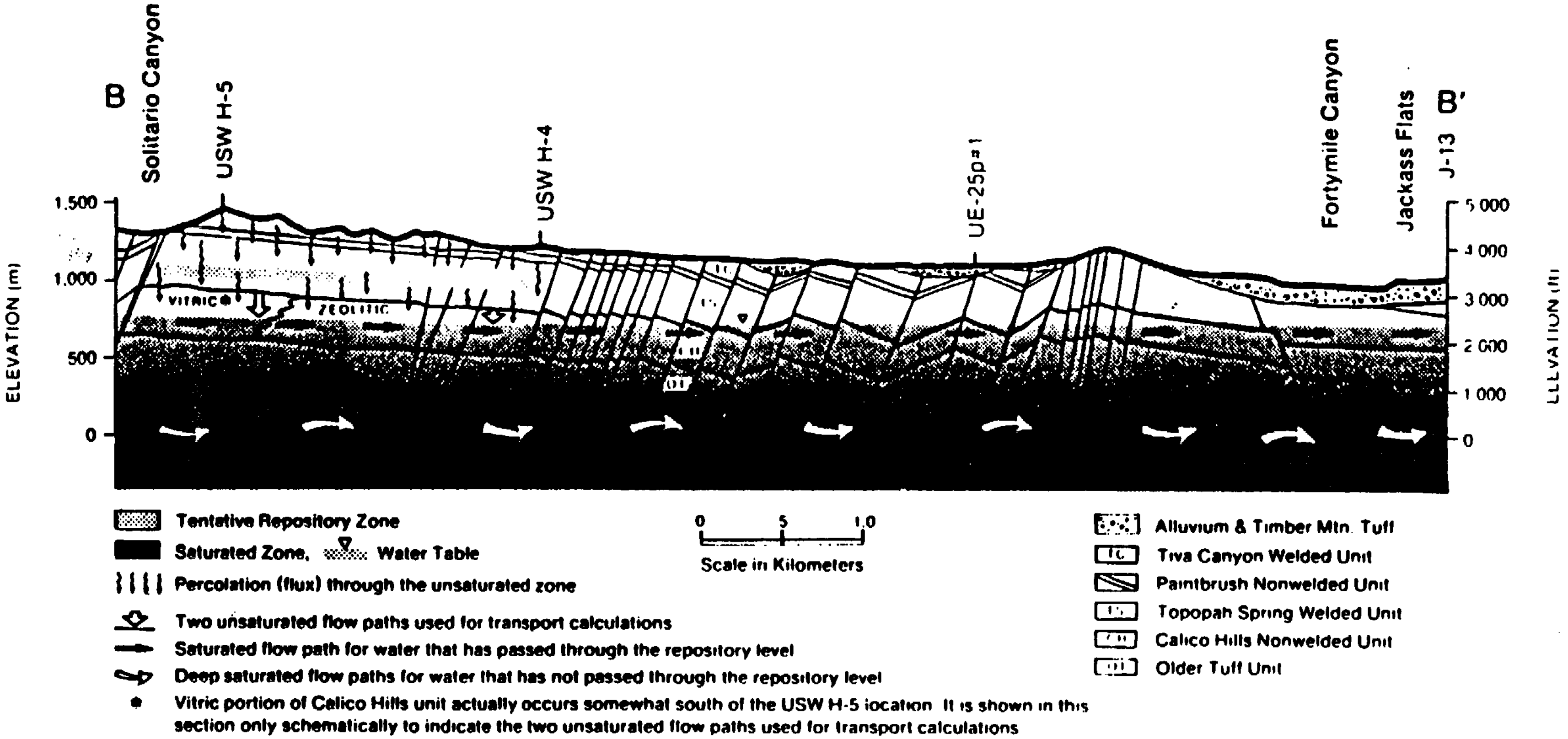


Figure 3. General hydrogeologic cross section of Yucca Mountain showing the anticipated flow paths from a potential repository to the water table and along the top of the saturated zone toward the accessible environment; UE-25p#1, USW H-4, and USW H-5 denote boreholes used for stratigraphic and water table control points; see Figure 6 for location of the section line.

Table 2. Relation of stratigraphic and hydrogeologic units at Yucca Mountain.

STRATIGRAPHIC UNIT			HYDROGEOLOGIC UNIT	APPROXIMATE THICKNESS (METERS)	COMMENTS
Alluvium			Alluvium	0-30+	Underlies washes; thin layer on flats.
Tiva Canyon Member			Tiva Canyon welded unit	70-150	Densely to moderately welded caprock that dips 5-8° eastward at Yucca Mountain; high fracture density.
Paintbrush Tuff	Pah Canyon Member		Paintbrush nonwelded unit	0-200	Vitric, nonwelded, porous, poorly indurated, bedded in part; low fracture density.
Paintbrush Tuff	Yucca Mtn. Member				
Paintbrush Tuff	Topopah Spring Member	Nonwelded			
Paintbrush Tuff	Topopah Spring Member	Vitrophyre Welded Vitrophyre	Topopah Spring welded unit	290-360	Densely to moderately welded; several lithophysal (cavity) zones; high fracture density; central and lower part is candidate host rock for repository.
Paintbrush Tuff	Topopah Spring Member	Nonwelded	Calico Hills nonwelded unit (Vitric) (Zeolitic)	100-400	Base of unit is determined by the water table; vitric in southwest Yucca Mountain, zeolitic in east and north.
Tuffaceous Beds of Calico Hills		Vitric Zeolitic	Water Table		
Crater Flat Tuff	Prow Pass Member	Nonwelded Welded	Older tuffs	> 1200 m	In USW H-1, lower part has hydraulic head about 50 m higher than water table at USW H-1.
Crater Flat Tuff	Bullfrog Member				
Crater Flat Tuff	Tram Member				
Lava					
Lithic Ridge Tuff					
Older Volcanics					
Pre-Tertiary Rocks			Pre-Tertiary Rocks	Unknown	Silurian carbonate occurs 2.5 km east of proposed repository at depth of 1,250 m in UE-25p#1 where hydraulic head is about 20 m higher than water table.

Table 3. Inferred hydrologic properties of the matrix and fractures of the hydrogeologic units at Yucca Mountain.

	MATRIX PROPERTIES						
HYDROSTRATIGRAPHIC UNIT	Estimated Bulk Porosity (% ±1)	Saturated Effective Porosity (%)	Average Saturated Hydraulic Conductivity (cm/sec)	Average Saturated Hydraulic Conductivity (mm/yr)	Saturation (% of Bulk Porosity ± 1)	Approximate Matric Potential (cm)[19]	Approximate Effective Hydraulic Conductivity (mm/yr)[20]
Tiva Canyon Densely Welded	10 ± 5.3[1]	5-8	2.5×10^{-9}[7]	0.8	72[13]	-10,000	0.025
Paintbrush Nonwelded	45 ± 11.8[2]	20-30	2.4×10^{-6}[8]	760	56 ± 17[14]	-8,000	150
Topopah Spring Densely Welded	15 ± 5.1[3]	8-12	3.5×10^{-9}[9]	1.1	69 ± 15[15]	-20,000	0.05
Calico Hills (Vitric)	39 ± 7.7[4]	20-30	1.3×10^{-6}[10]	410	NA[16]	-	--
Calico Hills (Zeolitic)	30 ± 8.6[5]	10-20	4.2×10^{-9}[11]	1.3	92 ± 5[17]	-20,000	0.05
Older Tuffs	23 ± ? [6]	5-15	1.1×10^{-7}[12]	35[12]	89 ± 8[18]	NA	35

(1) average of 11 samples
(2) average of 15 samples
(3) average of 51 samples
(4) average of 4 samples
(5) average of 27 samples
(6) average of 67 samples
(7) log average of 10 samples; 3 samples tested at lower limit of apparatus
(8) log average of 6 samples; 1 sample tested at lower limit of apparatus
(9) log average of 22 samples; 1 sample tested at lower limit of apparatus
(10) log average of 5 samples
(11) log average of 17 samples; 4 samples tested at lower limit of apparatus
(12) log average of 33 samples, unit is saturated, fracture flow dominates
(13) only 1 sample available
(14) 5 samples
(15) 27 samples
(16) no data available
(17) 5 samples
(18) 14 samples; unit is beneath the water table and therefore saturated though some small pores may not allow water to enter, low saturation may also indicate measurement bias
(19) representative samples used; from Peters (1984)
(20) representative samples used; from Peters and Gauthier (1984)

(See FRACTURE PROPERTIES on following page.)

the deepest stratigraphic unit completely above the water table in the potential area of waste emplacement. The lower part of this unit is beneath the water table in restricted locations several kilometers east of the Yucca Mountain site.

The nonwelded Calico Hills unit underlies the target host rock. It is divided into two distinct subunits, vitric and zeolitic (Tables 2 and 3). Though the two subunits occur at the same stratigraphic level (Figure 3), they are considered distinct hydrogeologic units because they have significantly different capabilities to transmit water through the rock matrix. The vitric part occurs beneath the southwest portion of the potential emplacement area and has hydrologic properties similar to those of the nonwelded Paintbrush unit, i.e., low fracture density and high saturated hydraulic conductivity (Table 3). The zeolitic part occurs beneath the north and east portions of the potential emplacement area and has low fracture density, similar to that of the vitric part and the nonwelded Paintbrush unit, and low matrix-saturated hydraulic conductivity, similar to that of the densely welded units. Bulk porosity is generally high, 30% to 40%, throughout the Calico Hills units, though perhaps somewhat higher in the vitric unit than the zeolitic unit. Effective porosity is assumed to be about 20% to 30% in the vitric unit and 10% to 20% in the zeolitic unit (Table 3). Both units appear to be nearly saturated. The water table at Yucca Mountain generally occurs within the Calico Hills unit.

The lowermost unit in the flow system between the proposed repository and the accessible environment

Table 3 (continued)

HYDROSTRATIGRAPHIC UNIT	FRACTURE PROPERTIES						
	Approximate Density (per m^3)(21)	Bulk Saturated Hydraulic Conductivity (mm/yr)	Calculated Effective Aperture (microns)(26)	Calculated Effective Fracture Porosity (%)(27)	Calculated Aperture(μ)(28) Required to Pass a Flux of 1 mm per/yr	5 mm per/yr	10 mm per/yr
Tiva Canyon Densely Welded	20	365,000(22)	89	0.0018	1.2	2.1	2.7
Paintbrush Nonwelded	10	75,000(23)	66	0.0007	1.6	2.7	3.4
Topopah Spring Densely Welded	40	365,000(24)	71	0.0028	1.0	1.7	2.1
Calico Hills (Vitric)	5	75,000(24)	83	0.0004	2.0	3.4	4.6
Calico Hills (Zeolitic)	5	75,000(25)	83	0.0004	2.0	3.4	4.6
Older Tuffs	5 20	75,000 - 365,000(25)	83-89	0.0004 0.0018	NA	NA	NA

(21) From Scott et al. (1983) rounded to nearest 5
(22) Assumed equal to saturated Topopah Spring
(23) Assumed equal to Calico Hills and Older Tuffs
(24) Representative value from well J-13 (Thordarson, 1983)
(25) Representative value from well J-13 (Thordarson, 1983), H-1, (Barr, 1984)
(26) Aperture, $b = (12ps)^{0.333} \times 10^6$, s = distance between fractures in meters obtained from one divided by fracture density, p = permeability in m^2 or 3.2×10^{-16} times conductivity in mm/yr (from Freeze and Cherry, 1979)
(27) Calculated effective porosity = fracture density x aperture in microns x 10^{-6}
(28) Assume all fractures participate in flow where permeability = 3.2×10^{-16} times flux in mm/yr, and aperture is calculated as per note 26

is designated as older tuff. It occurs exclusively beneath the water table throughout the Yucca Mountain site. Its top corresponds to the uppermost, moderately to densely welded layers in the Prow Pass or Bullfrog Members of Crater Flat Tuff (Table 2). It is slightly to densely fractured, and matrix hydraulic conductivities generally fall between those of densely welded and nonwelded units. Bulk porosity is about 25%. Because this unit is entirely below the water table, it is fully saturated (Table 3).

Local variation of hydrologic properties within each of the units is certain. These variations influence the details of local flow, but site characterization to date is not sufficient to reliably map them. Future characterization will decrease, but not eliminate, uncertainty about the distribution of heterogeneity within each unit. However, intraunit variations are almost certainly less influential on general flow conditions than variations among units because the differences of properties within units are much less than the differences among units. For this reason, we conclude that the gross behavior of the flow system can be reasonably approximated by assuming uniformity within each hydrogeologic unit.

The structural environment at Yucca Mountain may strongly influence groundwater flow through each of the units, particularly if the amount of flux through the unsaturated zone is large enough to cause flow through fractures. Accordingly, the structural features of primary interest are related to the distribution, density, orientation, and size of fractures throughout the site. The fractures in turn, are strongly related to the block-faulted nature of the Yucca Mountain area and to the degree of welding of the stratigraphic units.

Major faults, with up to a few hundred meters of vertical offset, have created a series of east-tilting blocks, hundreds to thousands of meters wide and several kilometers long (Figure 4). The reference emplacement area is within the informally designated central block (Figure 4), which dips eastward about 5° to 8°. This block is bounded on the west by a large fault zone along Solitario Canyon. To the east, it is bounded by several smaller, closely spaced faults or fracture sets. The northern edge is defined by Drill Hole Wash, an informally named canyon along a zone of possible strike-slip faulting or dense fracturing.

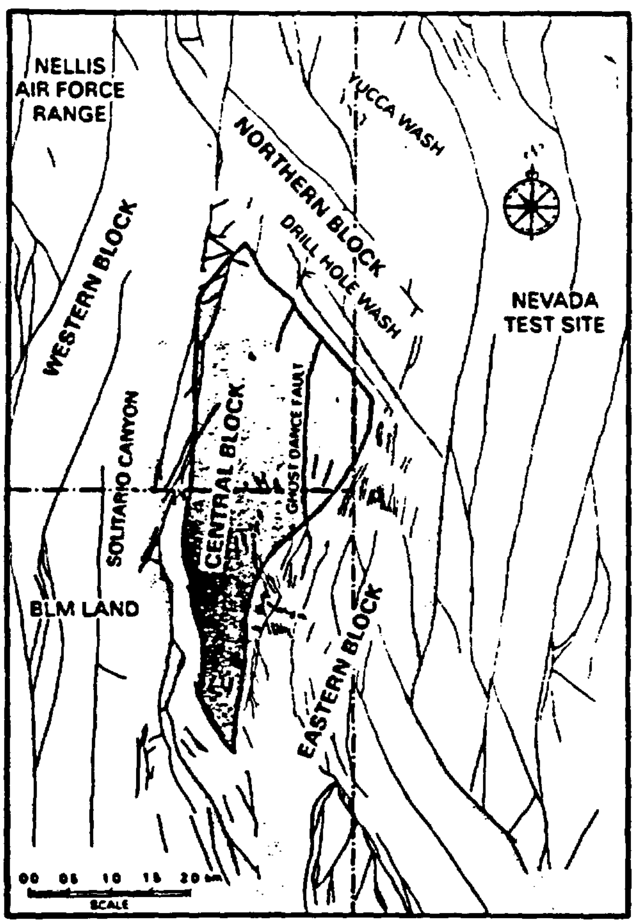


Figure 4. Major, informally designated structural blocks at Yucca Mountain and their relation to individual faults exposed in the ranges and inferred where buried by alluvium.

The southern boundary is less well defined, but generally occurs where the east- and west-bounding fault zones converge sufficiently to make the block too narrow for practical extension of emplacement drifts. Several minor faults with little vertical offset occur within the central block. The largest is informally named the Ghost Dance Fault (Figure 4). It has a maximum displacement of about 15 m near its central point and diminishes to no offset within a few hundred meters to the north and south.

The major block-forming faults surrounding the site generally trend just east of north and may serve as preferential groundwater flow conduits, particularly for horizontal flow in the saturated zone and perhaps for vertical flow in the unsaturated zone. Fractures observed at the surface trend predominantly north to northwest (Scott et al., 1983). The density of fractures generally increases with the degree of welding and is probably somewhat uniform within each structural block for each stratigraphic unit. Near major faults and local areas of abundant small faults, fracture densities probably increase. As with intraunit stratigraphic variations, the influences of local variations in fracture density probably can be ignored because the effects of major structures and stratigraphic distinctions dominate the general flow conditions at the site.

3.1.2 Groundwater Flux

Water that infiltrates at the surface and percolates through the stratigraphic and structural fabric of the site determines the unsaturated flow environment at Yucca Mountain. The amount of deep infiltration (unsaturated flux) is one of the most important and favorable aspects of Yucca Mountain, when considered as a repository site. Because the repository, if built, would be situated in the unsaturated zone, the total amount of water available to dissolve and transport the waste is limited to the amount of deep infiltration from the surface.

Several approaches are available to estimate the amount of unsaturated flux. The first is based on information about climatic conditions, vegetation, topography, and soil conditions. Under this approach, infiltration is calculated by subtracting the amount of surface runoff plus evapotranspiration from the amount of precipitation, which increases with elevation in southern Nevada. Soil conditions, topography, temperature, humidity, and vegetation are used to estimate runoff and evapotranspiration throughout the year. Based on this method, Rice (1984) estimated that infiltration for a large region surrounding

Yucca Mountain is less than 0.1 inch (~2.5 mm)* per year, though the study area was not small enough to indicate how much less occurs at Yucca Mountain.

Several investigators have used a similar, though perhaps less formal, approach which combines considerations of the mass balance between recharge and discharge in groundwater basins (water budgets) with assumptions about the locations of recharge based on elevation-determined climatic conditions. Using this approach, Eakin and others (1963), Walker and Eakin (1963), Mifflin (1968), and Waddell (1982) assumed that no recharge occurs at Yucca Mountain or in similar, nearby climatic zones. Rush (1970) used a method devised by Eakin and others (1951) to estimate that less than 3% of the precipitation in the Yucca Mountain region infirates deeply enough to recharge the saturated zone at elevations less than 5000 ft (~1500 m). Blankenagle and Weir (1973) used the same method to arrive at an estimate that only 2% of the precipitation in the 6000- to 7000-foot (~1800- to 2100-m) elevation range at Pahute Mesa percolates deeply enough to recharge the saturated zone. Rush's approach (Rush, 1970) provides the more conservative basis for establishing an upper bound for recharge of about 4 mm/yr for the 1200- to 1500-m elevation range at Yucca Mountain, where precipitation is estimated by Quiring (1965) to be about 6 to 8 in/yr (~150 to 200 mm/yr) (i.e., recharge is somewhat less than 4.5 to 6.0 mm/yr). On the basis of water-budget evaluations of the regional flow system, Rush assumed, along with Waddell and the others mentioned above, that the actual quantity of recharge in acre feet from this elevation zone was negligible.

The water-budget considerations of all these investigators indicate that no recharge is required from Yucca Mountain or similar climatic environments to explain the overall behavior of the regional flow system. We conclude that reasoning based on climatic information in combination with water-budget considerations indicates an upper bound of a few millimeters per year for the flux through the unsaturated zone at Yucca Mountain.

Two other approaches to estimating unsaturated flux are based directly on site-specific information. One infers vertical flux from measurements of the geothermal gradient, the variation of temperature with depth; the other infers flux from moisture contents and hydraulic pressures in rocks from the unsaturated zone. Using the geothermal approach, Sass and Lachenbruch (1982) estimated that water is moving downward at a rate of 1 to 10 mm/yr in the lower unsaturated zone and upper saturated zone at borehole USW G-1 in Drill Hole Wash. For shallow holes that penetrate only the upper portion of the unsaturated zone beneath Drill Hole Wash, geothermal data suggest a negative (upward) flux of up to tens of millimeters per year. These estimates are based on assumptions about the local geothermal flux and generalized data for the thermal conductivity of the stratigraphic units. Given the uncertainties due to the assumptions and generalizations, combined with the range of estimated flux for different locales, this method is currently unable to determine local flux within a narrow range. However, the geothermal approach does provide independent estimates of recharge that strengthen evidence that it is very low, certainly less than 10 mm/yr and probably less than 1 mm/yr.

The final approach to estimating flux through the unsaturated zone is based on measurements of moisture contents, hydraulic pressures, and effective hydraulic conductivities of rocks along unsaturated flow paths. This approach provides the most direct evidence about unsaturated water flux. For unsaturated material, openings exert a pull or suction on water which is inversely proportional to the size of the openings. This suction is due to capillary or surface-tension forces. These forces create negative pressures that tend to draw water into the rock matrix and hold it there. The lower the saturation or the less water there is in a rock of a given porosity, the greater is the capillary suction, because at lower saturations smaller voids with stronger capillary pull exert the negative pressure. Therefore, effective hydraulic conductivity also decreases as saturation decreases.

Measurements on core from Yucca Mountain indicate that saturation of the potential host rock, the Topopah Spring Member, is about 70% (Blair et al., 1984). Substantiating evidence currently is being obtained from in situ pressure-head measurements of -20 to -40 bars (about -20,000 to -40,000 cm of water) for the Topopah Spring Member in hole USW UZ-1 at Drill Hole Wash just north of the target emplacement area (P. Montezar, USGS, personal communication). These suction pressures correspond to saturations of less than about 50% to 80% based on moisture content-pressure head relations determined from core samples by Blair and others (1984) (Figure 5). The corresponding hydraulic conductivities are of the order of 0.01 to 0.1 mm/yr (Figure 5), indicating that 0.5 mm/yr constitutes a conservative upper limit on the flux through the rock matrix at the repository level (Peters, 1984).

*Metric units are generally used in this report unless the original data from previous studies are being described; in these cases metric conversions are provided

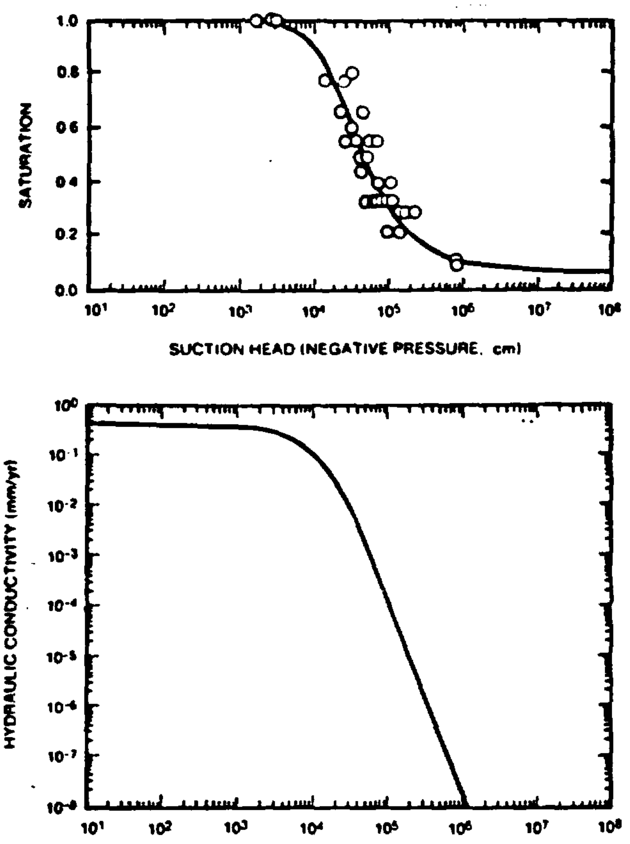


Figure 5. Relations between saturation, hydraulic conductivity, and suction head; bottom curve (from Peters and Gauthier, 1984) calculated from best-fit upper curve (from Peters, 1984); upper curve generated from measurements represented by circles (from Blair et al., 1984) of a representative sample (G4-6) of the Topopah Spring welded unit.

Because the Topopah Spring Member is fractured, it is possible that some of the flux moves through fractures in the unsaturated zone. Two lines of evidence show, however, that this is unlikely. First, calculations by Travis and others (1984) indicate that water moving through fractures with apertures as small as 100 μm would be unable to penetrate more than a few meters, at most, through fractured, densely welded tuff with matrix saturations as high as 90%, and it would penetrate even shorter distances for lower saturations or smaller fracture apertures. Under matrix suction pressures corresponding to saturations of 90% or less, all water in the fractures would be drawn into the rock as the water moved short distances through the fractures. Wang and Narasimhan (1984) calculate a pressure range over which the transition from fracture flow to matrix flow would occur in jointed blocks composed of densely welded tuff. They predict the transition will occur abruptly at negative matrix pressures of about a few tens of centimeters of water, far higher than the observed pressures at Yucca Mountain. The hydraulic conductivity (the same as effective flux, given a gradient of 1) corresponding to the calculated pressure threshold for fracture flow is about 0.5 to 1 mm/yr. The calculations by Travis and others (1984) and Wang and Narashimhan (1984) indicate that the low moisture contents observed in the host rock will prohibit any substainable flow through the fractures in the unsaturated zone.

The second line of evidence is provided by Peters and Gauthier (1984), who calculate that flux in excess of about 0.5 mm/yr would nearly saturate most rocks in the unsaturated zone at Yucca Mountain, including the Topopah Spring Member. If the rocks were initially of low saturation and sustained fracture flow were to occur, water drawn from the fractures into the matrix would completely saturate the matrix under a flux of about 0.5 mm/yr. Thus, according to Peters and Gauthier (1984), a flux in excess of about 0.5 mm/yr would produce a higher moisture content and lower suction pressure than the values observed at Yucca Mountain. Only if higher moisture contents and lower suction pressures were to occur would the fractures be able to sustain water flow, as pointed out by Travis and others (1984) and Wang and Narashimhan (1984).

Concentrations of infiltration in time or space may seem to provide a means of supplying enough flux to cause fracture flow in limited portions of the site. This may seem particularly likely beneath the washes which concentrate runoff and, hence, moisture available for infiltration along or across fault zones or other densely fractured locations. However, a logical consequence of this situation would be a horizontal pressure gradient away from the limited zones of fracture flow and the adjacent, nearly saturated rock toward zones where no fracture flow occurs and the rock matrix is less saturated. It is unlikely, though not certain, at this time, that such a gradient could be maintained for very long, because the pore water would tend to migrate along the gradient through the matrix in an attempt to establish an equilibrium pressure that would eliminate the gradient. Given this reasoning, we tentatively conclude that pulses of flux through fractures at restricted places are not very likely, at least not as episodic events occurring at regular and frequent intervals at the same place. This conclusion needs to be confirmed by detailed modeling that calculates the lateral gradients of moisture content and pressure, if any, that can be sustained by local pulses of fracture flow of various intensities and frequencies.

At the current time, data on moisture content in the unsaturated zone strongly indicate that sustained, widely distributed fracture flow is a not a credible process at Yucca Mountain. As a result, the average flux is probably limited to a value equal to the hydraulic conductivity of the matrix under the suction heads of 20,000 to 40,000 cm, corresponding to saturations of 85% or less. Though these values are not yet firmly established for all hydrogeologic units and undoubtedly vary within the units, the current data on hydraulic conductivities indicate that the average flux through Yucca Mountain is probably less than about 0.5 mm/yr, or about an order of magnitude less than the upper end of the range estimated from more indirect climatic, water-budget, or geothermal methods. Before this conceptual model of flux through the unsaturated zone can be firmly established, however, more widely distributed data are needed for in situ moisture contents, pressure heads, and hydraulic conductivities.

After water percolates vertically to the water table, it will mix with the water flowing into the site as underflow from recharge regions to the north. This underflow or flux through the saturated zone at Yucca Mountain has been estimated by Waddell (1982) to be on the order of 10^{-5} to 10^{-6} m^3/s for a 1-m-wide strip of saturated aquifer (Sinnock et al., eds., 1984). For a spot location at the northern end of the potential repository area, Waddell (1982) calculated a flux of about 2×10^{-6} $m^3/s/m$ per meter of aquifer width; for a spot location just southeast of the site, the calculated value is about 5×10^{-7} $m^3/s/m$. Waddell (1982) assumes all flux enters the site as underflow from recharge areas to the north, primarily at Pahute Mesa. Though considerable uncertainty is associated with these estimates because of the regional scale of the model that produced them, they are the only ones available and are presented here without further discussion. In the next section, the implications of these estimates are discussed with respect to attempts to estimate hydraulic conductivities in the saturated zone.

3.1.3 Groundwater Flow at Yucca Mountain

As outlined in Chapter 2, assumption 9, the velocity of water flow, Vw, in both the saturated and unsaturated zones is assumed to obey general Darcy principles, so the velocity is equal to the flux, F, divided by the effective porosity, n:

$$V_w = F/n \tag{1}$$

In the unsaturated zone, n is determined by the moisture content and degree of saturation of the rocks. This flux cannot exceed, but may be less than, the amount determined by the general Darcy equation

$$Q = K \cdot \frac{\partial h}{\partial l} \cdot A \tag{2}$$

where Q is the total volumetric rate of flow, K is the hydraulic conductivity, $\partial h/\partial l$ is the hydraulic gradient, and A is the cross-sectional area through which flow occurs.* The flux is the same as Q for a unit area of the total area, A.

3.1.3.1 Flow in the Unsaturated Zone

A flow system tends to adjust the basic flow parameters in a manner that enables the flux to be transmitted. In contrast to the saturated zone where the gradient generally adjusts to a minimum slope required to ensure that the flux is transmitted through various rocks, with a differing but fixed conductivity, the conductivity of a given rock in the unsaturated zone will tend to adjust to the minimum value required to transmit the flux under a gradient fixed by gravity at unity. This can occur because conductivity changes as the saturation changes, so, in effect, moisture contents will adjust to yield a conductivity equal to the flux, given a gradient of 1.

Two types of hydraulic conductivity, matrix and fracture, are pertinent to understanding water flow through the unsaturated rocks at Yucca Mountain. If the flux exceeds the matrix conductivity times the gradient, flow will be through fractures, which at Yucca Mountain generally have much higher conductivities and much lower effective porosities than the matrix (Table 3). Because effective porosities of fractures are generally low, velocities in fractures tend to be relatively rapid. The upper limit of matrix conductivity is set by its value under saturated conditions. The saturated matrix conductivity of the Tiva Canyon, Topopah Spring, and zeolitic Calico Hills units is about 1 mm/yr (Table 3). If flux is less than the saturated matrix conductivity, water will tend to flow relatively slowly through the high effective porosity of the matrix. It follows that flux through the unsaturated zone at Yucca Mountain in excess of the saturated matrix conductivity (gradient = 1) must pass through fractures, so that flux in excess of about 1 mm/yr would tend to cause fracture flow through the densely welded Tiva Canyon and Topopah Spring units and the nonwelded, zeolitic Calico Hills unit.

However, this excess flux would probably never exceed a few millimeters per year at Yucca Mountain,

*Conventionally, $\partial h/\partial l$ is taken to be a negative number because flow occurs from points of high to low head; for convenience we assume $\partial h/\partial l$ is positive and omit the minus sign from the Darcy equation averaged in time and space. The fractures in the densely welded units and zeolitic Calico Hills unit have a capacity to annually transmit tens of thousands of millimeters of water (Table 3). As a result, the relatively low flux in excess of the matrix capacity, were it to occur, would occupy only a small portion of the total fracture network, probably that portion composed of the narrowest interconnected apertures required to transmit the water (Table 3, last three columns). It is plausible that the small fractures participating in the flow for such small excess flux would behave more like pores in the matrix than the large fractures required to transmit a large flux in, for example, a saturated flow system. If the capillary forces in matrix pores and small fractures were similar, exchange of water between the two could occur, and the fractures would constitute an extension of the effective porosity of the matrix necessary to establish a conductivity just sufficient to pass the flux by "porous" flow. As a result, effective porosity may not drop precipitously, and may even increase slightly, upon initiation of fracture flow.

Flux necessary to initiate fracture flow, i.e., greater than about 1.0 mm/yr, is unlikely, as discussed in Section 3.1.2, because of the apparent low saturation and corresponding effective conductivity of the Topopah Spring Member. The preliminary nature and sparse distribution of saturation and conductivity data do not allow complete dismissal of a higher flux, at least in portions of the site not tested for saturation values. Even for the unlikely event where flux exceeds the carrying capacity of the matrix of the densely welded and zeolitic units, the nonwelded, nonzeolitic units, with matrix conductivities of several hundred to a thousand millimeters per year, could pass the water through pores in the matrix, thereby precluding significant fracture flow through these units.

If the climate were to change to wetter, pluvial conditions similar to those about 15,000 yr ago, more infiltration might occur, and water might be able to pass through the fractures after saturating the matrix. Based on the interpretation of fossil-plant remains from pack-rat middens, Spaulding (1983) reasons that pluvial climates at Yucca Mountain were similar to these now occurring 1000 or 2000 ft higher, analogous to the present climate on Pahute Mesa. Blankenagel and Weir (1973) estimate that 2% of precipitation or about 1400 acre-ft ($\sim 1.7 \times 10^6$ m^3) of recharge occur there annually in the 6000- to 7000-foot ($\sim$1800- to 2100-m) elevation range over an area of 95,000 acres ($\sim 3.8 \times 10^8$ m^2). This is equivalent to an average flux of about 4.5 mm/yr. Rush (1970) estimates recharge in the 6000- to 7000-foot ($\sim$1800- to 2100-m) elevation zone to be 7% of precipitation, which Quiring (1965) estimates to be about 8 to 12 in/yr (200 to 300 mm/yr), yielding a flux of about 14 to 21 mm/yr. This information leads us to a preliminary conclusion founded on conservative estimates that no more than 10 or 20 mm/yr of flux would be available to pass through the unsaturated zone at Yucca Mountain under wetter climates.

However, high, past flux implies certain logical consequences that may constrain estimates of the effects of pluvial conditions on flux at Yucca Mountain. If flux through the unsaturated zone were more than a few millimeters per year during the last pluvial episode, which lasted several decamillenia and ended about 10,000 to 12,000 yr ago (Spaulding, 1983), the matrix of the rocks would have been nearly saturated because of the principles discussed above. When the pluvial climate ended and infiltration slowed, the rock matrix would have drained by matrix flow to the level of saturation observed today. Given the low matrix conductivity and thickness of the densely welded units, such a draining process (from nearly 100% to 85% or less saturation) may have required more time under a prevailing flux than has been available since the end of the last pluvial episode. Detailed modeling of this drainage problem at Yucca Mountain has not been undertaken, but it must be considered when attempting to establish the likely change in flux through the unsaturated zone due to the potential onset of another pluvial climate.

Thus, the velocity of flow through the unsaturated zone and the corresponding water travel times at Yucca Mountain depend heavily on the flux caused by deep infiltration. If it is less than about 0.5 mm/yr, the most likely case, flow probably will be exclusively through the pores of the rock matrix, and travel times through all units will be very long. If the current flux is higher than presently thought or if it were to increase in the future, movement of water through the unsaturated zone might occur by both fracture and matrix flow. The north and east portions of the waste-emplacement area are underlain by the zeolitic Calico Hills unit, and flow to the water table in those portions probably would be almost entirely by rapid fracture flow for flux in excess of about 1 mm/yr. Flow time in the south and west portions of the emplacement area would be dominated by slow flow through the matrix of the vitric Calico Hills unit, even for credible increases in flux caused by a recurrence of pluvial climates.

3.1.3.2 Flow in the Saturated Zone

In the saturated zone, almost all flow beneath the repository site is probably through fractures. The parameters necessary for determining saturated flow velocities are expressed by

$$V_w = \frac{Ki}{n} \quad (3)$$

where V_w is the particle velocity for water, K is the hydraulic conductivity, i is the hydraulic gradient ($\partial h/\partial l$), and n is the effective porosity of fractures; or from

$$V_w = \frac{F}{n} \quad (1)$$

where F, the flux, is equal to the hydraulic conductivity times the gradient.

The horizontal component of the hydraulic gradient in the central and east portions of the site is generally well established as about 0.00034 from observations of static-water levels in several drill holes throughout the Yucca Mountain area (J. H. Robison, USGS, personal communication) (Figure 6), though local variations from the regional gradient are likely. Preliminary data on head variations with depth indicate that the saturated volcanic rocks behave as an unconfined aquifer because head is nearly constant through the upper few hundred meters of aquifer thickness

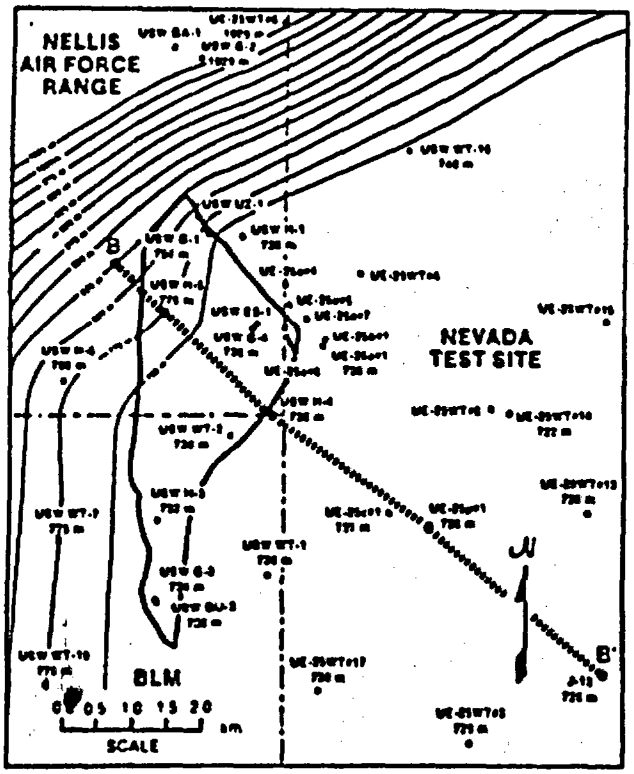


Figure 6. Water table contours and spot, static-water levels in drill holes at Yucca Mountain; B-B' shows the location of the hydrogeologic cross section in Figure 3.

(J. H. Robison, USGS personal communication). Deeper in the volcanic section, head may increase, as indicated by measurements in drillhole USW H-1 (Rush et al., 1983). A carbonate aquifer occurs at a depth of about 1400 m in one drillhole, Ue25p#1, and exhibits higher head than the overlying, unconfined volcanic aquifer (J. H. Robison, USGS, personal communication). Thus, a confined aquifer may occur deep beneath the water table at Yucca Mountain, but recharge from the unsaturated zone should flow nearly horizontally at the water table along the gradient of the generally unconfined volcanic aquifer.

The effective porosity of fractures, though less well established than the gradient, probably falls within limits ranging from about 0.0005 to 0.005. These numbers are based on calculations of fracture apertures required to produce the rock-mass permeability for a given number of fractures per unit volume of rock (Table 3). This range is considerably less than the estimate by Thordarson (1983) of several percent for the effective porosity of the rock matrix of core samples and coincides at its upper end with the value estimated for fracture-flow systems in tuff by Blankenagel and Weir (1973).

The range of hydraulic conductivity for rocks along the saturated flow path is more difficult to determine. Carbon-14 ages of groundwater in the vicinity of Yucca Mountain (Figure 7) indicate that actual

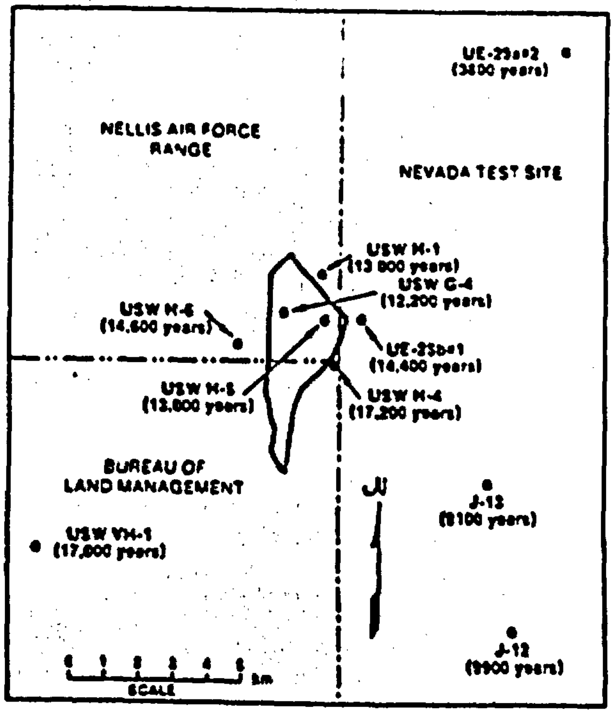


Figure 7. Groundwater ages determined by uncorrected C-14 dating of water samples from the saturated zone at selected drill holes in the vicinity of Yucca Mountain (from Benson et al., 1983)

saturated-flow velocities are about 1 to 5 m/yr (Benson et al., 1983). These values yield saturated flow times of 2000 to 10,000 yr for 10 km. Assuming an effective porosity of 0.002 and a higher gradient of 0.001 to account for increasing water table levels north of Yucca Mountain, the groundwater ages suggest that the average effective conductivity is on the order of 25 m/yr.

A single aquifer test in well J-13 yielded an estimate of 1 m/d (365 m/yr) for the hydraulic conductivity of the Topopah Spring Member (Thordarson, 1983), which occupies about 30% to 40% of the flow path of concern (Figure 3). The rest of the saturated flow path is through the Calico Hills unit or older tuff. Hydraulic conductivities of these two units have been estimated from tests of nine packed-off test intervals in well J-13. The estimates range from 0.0057 to 0.15 m/d (about 2 to 50 m/yr) (Thordarson, 1983) with a logarithmic average of about 0.01 m/d (about 4 m/yr). Based on aquifer tests in well USW H-1, conductivities for the Calico Hills unit and older tuff range from about 0.0002 m/d (about 0.07 m/yr) to about 2 m/d (about 700 m/yr) (Rush et al., 1983; Barr, 1984). The lower values correspond to tests of either isolated depth intervals of several hundred meters occurring 600 m or more beneath the water table or of composite intervals 1000 m or more thick and excluding the upper few hundred meters of aquifer. The higher values from drillhole USW H-1 correspond to the upper 100 m or so of the saturated zone. The Topopah Spring Member is not saturated in USW H-1, so no conductivity estimates for it are available from the general area where waste would be emplaced.

The well tests show that high conductivity values of tens to hundreds of m/yr occur only at isolated depth intervals of single wells. These intervals are generally near the water table (Benson et al., 1983) and are probably characterized by unusually dense or open fractures. Several tests suggest that homogeneous conductivity is also limited horizontally to zones a few hundred meters in extent (Barr, 1984). In conjunction with data on groundwater ages, this information leads us to conclude that hydraulic conductivities of about 1 to 50 m/yr probably bound the range of effective values for flow paths greater than a few hundred to a thousand meters or so.

Another line of reasoning leads to much higher estimates of effective saturated conductivities. Because saturated flux through a unit area is equal to the hydraulic conductivity times the gradient, the values for conductivity assumed above, 1 to 50 m/yr, yield a unit flux of about 1×10^{-11} to 5×10^{-10} $m^3/s/m^2$ for a gradient of 0.00034. According to the flux estimates of about 2×10^{-6} and 5×10^{-7} m^3/s per meter of aquifer width at point locations at Yucca Mountain (Waddell, 1982), the saturated flow regime would require more than 1000 to over 200,000 m of aquifer thickness, a ridiculous range, to transmit the total flux, given a conductivity of 1 to 50 m/yr. Because the regional gradient is known with relatively high confidence, the total flux calculated by Waddell (1982) would require conductivities on the order of several thousand meters per year, assuming a reasonable aquifer thickness of less than a few hundred meters.

Observations that most flow occurs in intervals less than 100 m thick, which commonly are dispersed only throughout the upper few hundred meters of the saturated zone (Benson et al., 1983), mean that either total aquifer flux is about 10 to 100 times less than estimated by Waddell (1982) or the hydraulic gradient times the hydraulic conductivity is 10 to 100 times greater than indicated by groundwater ages and aquifer tests. We believe that the lower conductivity estimates based on field data for groundwater ages and aquifer conductivities represent the situation at Yucca Mountain better than those inferred from regional flux estimates. This is because the regional estimates are based on large-scale modeling, which requires very broad assumptions and generalizations about hydrologic conditions. In contrast, the lower estimates of hydraulic conductivity are based on field data obtained at and near the Yucca Mountain site. However, even the lower estimates represent a significant capacity to transmit water.

Even for the low hydraulic gradient observed from drillholes throughout the Yucca Mountain area, saturated flow velocities are probably still high and saturated flow times to the accessible environment (at the end of 2- or 10-km flow paths) short as a result of high conductivities and low fracture porosities. If the high conductivities calculated from drill-stem tests and regional flux estimates are not continuous along individual flow paths, the total flux through the saturated zone may be less than currently estimated by Waddell (1982). In this case, average flow velocity might be dominated by slow flow through interspersed, less conductive portions of the flow path. This situation could occur if interconnected, high fracture conductivity is restricted laterally and vertically to isolated zones and the bulk of the gradient drop occurs in regions between these zones.

Though considerable uncertainty is associated with the hydraulic conductivity in the saturated zone, it does not contribute much to uncertainty about total flow time from a repository to the accessible environment if unsaturated flux is less than about 1 mm/yr. Such low flux through the unsaturated zone will yield flow times of tens of thousands of years, so the additional few hundred or thousands of years in the saturated zone would not significantly affect total flow time even if the accessible environment were to occur at the end of a 10-km saturated flow path.

In summary, the hydrologic environment at Yucca Mountain, particularly the unsaturated zone, offers a highly promising barrier for isolating wastes for very long times. However, under certain plausible, but unlikely, conditions of unsaturated flux greater than the maximum hydraulic conductivity of the matrix, currently believed to be about 1 mm/yr, groundwater flow from parts of the repository to the water table might be relatively rapid, though the total amount of water moving through the repository would remain small, i.e., a few millimeters per year. Only under such unlikely conditions of flux would the saturated flow regime contribute significantly to total flow time to the accessible environment.

3.2 GEOCHEMISTRY

The geochemical information needed for analysis of repository behavior is that which influences waste solubility and radionuclide transport. The geochemical conditions of primary concern for waste solubility are the Eh, pH, and dissolved solids of groundwater. These items are discussed in Section 3.2.1. Conditions that will influence radionuclide transport are discussed in Section 3.2.2; they determine how effectively the rocks will be able to retard radionuclide migration.

3.2.1 Solubility

Though waste solubility will be affected by elevated temperatures caused by radioactive decay of the waste, it probably will be similar at the close of the containment period (300 to 1000 yr) to what it would be under current, ambient temperatures. This assumption is part of the broader general assumption given in Chapter 2, assumption 6. It is based on predictions of temperature histories for a repository in densely welded tuff (Peters, 1983; Johnstone et al., 1984; Klasi et al., 1982; Johnson, 1982; Sundberg and Eaton, 1982) that indicate temperatures less than 100°C will occur at the wall of emplacement holes before the end of the containment period, even if it lasts only 300 years. Because temperatures of less than 100°C are not expected to cause significant changes in the geochemical environment, we tentatively conclude that decay heat from the waste will not significantly affect waste solubility. Accordingly, our analyses of waste dissolution are based on information about geochemical conditions that currently exist in the host rock.

No data are available on the chemistry of water from the target emplacement horizon because of the difficulty of obtaining water samples from the unsaturated zone. However, chemical analyses of water samples from tuffaceous aquifers in and around the site have been made (Benson et al., 1983). Assuming that water in these aquifers reached its present chemical condition, at least in part, because it passed through rocks in or similar to those in the unsaturated zone at the site, the dissolved solids in the unsaturated zone should be similar to those in the saturated zone. Extrapolating the pH and, particularly, the Eh of the water from the saturated zone to the unsaturated zone is more difficult to justify. Therefore, the following discussion of water chemistry at Yucca Mountain should be interpreted cautiously in light of the uncertainties associated with the correspondence between unsaturated and saturated conditions.

Generally, the water at Yucca Mountain is benign in terms of its inherent capability to dissolve nuclear waste in either glass or spent fuel forms (Kerrisk, 1984). The content of dissolved solids is generally a few hundred parts per million, predominantly sodium cations and bicarbonate anions (Table 4). The pH is nearly neutral (pH = 7) to slightly alkaline (pH < 8 or so) (Benson et al., 1983). Estimates of the Eh suggest that oxidizing conditions up to about 700 mV may occur. These estimates are based on an assumption that free oxygen is available from the atmospheric gases in the unsaturated zone and that the liquid water is saturated with oxygen.

Under these conditions the water at Yucca Mountain is geochemically suitable as an excellent source of drinking water. Its potential reactivity with emplaced waste would, by analogy, be similar to the corrosion occurring when a drinking glass is filled with aerated water from a typical kitchen faucet. During the long time desired for containment of the wastes in a repository, such rates would, of course, slowly dissolve some of the waste; the analogy is made only to point out that water at Yucca Mountain is not, in any sense, an unusually corrosive agent.

The solubility of uranium has been calculated by two geochemical models of equilibrium reactions using as a basis for computation the chemical characteristics of water from the saturated zone near the site (see data for Well J-13, Table 4) and on assumed oxidation and pH states (Figure 8). Wolfsberg and others (1982) and Daniels and others (1982) used the EQ3 model (Wolery, 1979) to estimate uranium solubilities alone and in the presence of plutonium.

Table 4. Chemical composition of water samples from selected drill holes in the vicinity of Yucca Mountain (from Benson et al., 1983).

Borehole	Onsite pH (units)	Laboratory pH (units)	Water Temperature (°C)	Dissolved constituents (mg/ℓ) Ca	Mg	Na	K	HCO_3 field	HCO_3 laboratory	Cl	SO_4	SiO_2	Li	Sr	F
UE-25b#1	7.1	6.8	36.0	19	0.73	53	3.7	173	158	13	24	53	0.950	0.044	1.5
UE-25b#1	7.5	7.5	36.0	17	0.59	46	3.5	139	134	8.5	22	52	0.220	0.038	1.6
UE-25b#1	7.1	7.7	37.2	18	0.72	46	2.8	133	138	7.5	21	51	0.120	0.047	1.6
UE-29a#2	7.2	7.6	25.1	10	0.2	44	1.1	107	112	11	22	44	0.100	0.039	1.0
UE-29a#2	7.0	7.4	22.7	10	0.3	44	1.3	107	110	8.8	21	44	0.110	0.033	.9
USW H-1	7.7	7.8	33.0	4.5	<0.1	51	2.4	---	115	5.7	18	47	0.040	0.005	1.2
USW G-4	7.7	7.5	35.6	13	0.2	57	2.1	139	143	5.9	19	45	0.067	0.017	2.5
USW H-1	7.5	8.0	34.7	6.2	<0.1	51	1.6	---	122	5.8	19	40	0.040	0.020	1.0
USW H-4	7.4	7.9	34.8	17	0.29	73	2.6	173	171	6.9	26	46	0.130	0.027	4.6
USW H-5	7.8	7.8	36.5	1.9	0.01	60	2.1	126	124	6.1	16	48	0.062	0.009	1.4
USW H-5	7.9	8.0	35.3	2.0	<0.01	60	2.1	127	124	6.1	16	48	0.071	0.004	1.4
USW H-6	8.1	8.3	37.8	4.1	0.09	86	1.3	182	188	7.6	29	48	0.082	0.008	4.7
USW VH-1	7.9	8.0	35.2	11	1.6	79	1.9	167	158	11	44	50	0.090	0.070	2.7
USW VH-1	7.5	7.9	35.5	10	1.5	80	1.9	165	158	10	45	50	0.090	0.070	2.7
USW VH-1	7.5	8.0	35.5	9.9	1.5	78	1.8	162	158	10	44	49	0.090	0.060	2.7
J-12	7.1	---	27.0	14	2.1	38	5.1	---	119	7.3	22	54	0.040	0.010	2.1
J-13	7.2	---	31.0	12	2.1	42	5.0	---	124	7.1	17	57	0.040	0.020	2.4

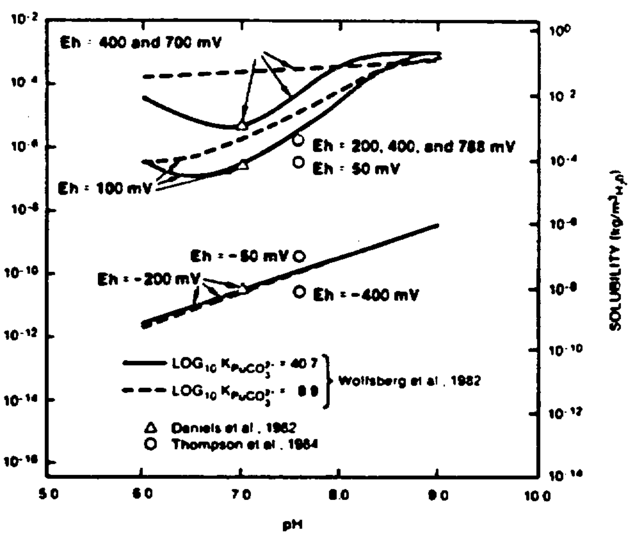


Figure 8. Solubilities of uranium calculated for various Eh and pH conditions in water with a composition similar to that from Yucca Mountain (J-13 water, see Table 4); (from Wolfsberg et al., 1982; Daniels et al., 1982; and Thompson et al., 1984).

Because plutonium tends to tie up most available carbonate as $PuCO_3^{2+}$, less uranium carbonate gets into solution than when plutonium is not present. As a result, uranium solubility for a pH of 6.9 and an Eh range of 700 to -200 mV was calculated to range from about 3.4 x 10^{-6} to 1.6 x 10^{-11} mol/ℓ in the presence of plutonium and from about 3.0 x 10^{-4} to 1.5 x 10^{-11} mol/ℓ if plutonium is absent. As the Eh increases, or if the equilibrium constant of $PuCO_3^{2+}$, is low (freeing carbonate in solution), the solubility of uranium increases (Figure 8). Using another geochemical model, MINTEQ (Felmy et al., 1984), Thompson and others (1984) calculated uranium solubilities of about 10^{-6} to 5 x 10^{-11} mol/ℓ for Eh values ranging from 788 to -400 mV, respectively, and a pH of 7.5 (Figure 8). These calculations indicate that under the probable pH and Eh conditions of the host rock at Yucca Mountain, the solubility of uranium in spent fuel would be less than about 10^{-4} mol/ℓ and perhaps as low as 10^{-6} or 10^{-7} mol/ℓ.

From assumption 5, Chapter 2, the annual dissolution rate of uranium, DR_u, will be

$$DR_u = S_u \cdot Q \qquad (5)$$

where S_u is the solubility limit of uranium expressed in kg/m^3 of water (mol/ℓ x 0.238 kg/mol x 1000 ℓ/m^3) and Q is the annual water flux in cubic meters interacting with the waste. For other waste species, i, the annual dissolution rate, DR_i, is then

$$DR_i = DR_u \, [M_i/M_u] \qquad (6)$$

where M_u and M_i are, respectively, the mass of uranium and the mass of species i in the spent fuel. An implicit assumption in this equation is that the release of all radionuclides from the repository will be limited by the solubility of uranium. This assumption is probably conservative because some waste species have lower solubilities than uranium (Kerrisk, 1984). For species with higher solubilities than uranium, including cesium and technetium, both the kinetic limitations on dissolution rates in flowing water and the generally homogeneous distribution of many of these species in the spent-fuel matrix are likely to slow effective dissolution rates to values more nearly congruent with uranium (Kerrisk, 1984; Braithwaite, 1984). Some species with higher solubilities than uranium may be somewhat segregated in the spent fuel, including carbon in the zircalloy cladding, iodine in the gaps between the fuel and cladding, and cesium in the fuel itself.

The oxidizing nature of the groundwater is a potentially adverse condition at Yucca Mountain that requires special attention. However, the low flux of water, in combination with potentially reducing environments provided by steel and zircalloy in the engineered barriers, will, in all likelihood, adequately compensate for the ambient oxidizing environment.

3.2.2 Radionuclide Retardation

In terms of potential effects on radionuclide transport, the geochemical environment is, perhaps, one of the most favorable aspects of the Yucca Mountain site. Assuming that groundwater flow, in conjunction with hydrodynamic dispersion, sets an upper limit on the velocity for dissolved radionuclides to move away from a repository, geochemical and related physical interactions among the wastes, groundwater, and surrounding rocks can only enhance site performance by slowing radionuclide movement. Processes such as mineral precipitation, ion exchange, absorption, and adsorption will slow the movement of radionuclides relative to groundwater flow. The characteristics of the rocks at Yucca Mountain are highly conducive to all these retardation processes. Though the differences among these processes are recognized, their combined effects on radionuclide movement are commonly referred to in this report as retardation, recognizing that the term sorption is generally reserved for a specific subset of reactions.

As mentioned in Chapter 2, assumption 10, the velocity of radionuclide movement relative to groundwater movement through the rock matrix is obtained by a retardation factor, Rd. For a particular radionuclide, i, assuming equilibrium conditions:

$$Rd_i = Kd_i(\gamma/n) + 1 \qquad (7)$$

where γ is the bulk density of the rock and n is the effective porosity, and Kd is the sorption ration, which depends on the rock and the radionuclide. The average velocity for a particular radionuclide, V_r, is then

$$V_i = V_w/Rd \qquad (8)$$

where V_w is the average particle velocity of water.

The relatively high porosity of the tuff units (Table 3), combined with the generally small size of the pores, offers a large surface area for geochemical and physical interactions between the rock and moving radionuclides. At least in part because of this structural fabric, sorption of radionuclides by the tuffs at Yucca Mountain, independent of mineralogical composition, will in all likelihood be very high. Values for the sorption ratio, Kd (expressed in ml/g), are generally more than 100 for cationic waste species, including cesium, strontium, plutonium, americium, barium, and tin (Table 5). For anionic species, such as technetium, iodine, and carbon, sorption ratios are generally low, i.e., less than 1, and may be

Table 5. Representative sorption ratios, Kd's, of selected radionuclides in the matrix materials of different rock units at Yucca Mountain (from Daniels et al., 1982; 1983).

Tuff unit	Waste element	Sorption ratio Kd (ml/g)
[illegible]	Americium (Am)	[illegible]
	Cesium (Cs)	[illegible]
	Neptunium (Np)	[illegible]
	Plutonium (Pu)	[illegible]
	Strontium (Sr)	[illegible]
	Technetium (Tc)	[illegible]
	Uranium (U)	[illegible]
	Barium (Ba)	[illegible]
[illegible]	Americium (Am)	[illegible]
	Cesium (Cs)	[illegible]
	Neptunium (Np)	[illegible]
	Plutonium (Pu)	[illegible]
	Strontium (Sr)	[illegible]
	Technetium (Tc)	[illegible]
	Uranium (U)	[illegible]
	Barium (Ba)	[illegible]
[illegible]	Americium (Am)	[illegible]
	Cesium (Cs)	[illegible]
	Neptunium (Np)	[illegible]
	Plutonium (Pu)	[illegible]
	Strontium (Sr)	[illegible]
	Technetium (Tc)	[illegible]
	Uranium (U)	[illegible]
	Barium (Ba)	[illegible]
[illegible]	Americium (Am)	[illegible]
	Cesium (Cs)	[illegible]
	Neptunium (Np)	[illegible]
	Plutonium (Pu)	[illegible]
	Strontium (Sr)	[illegible]
	Technetium (Tc)	[illegible]
	Uranium (U)	[illegible]
	Barium (Ba)	[illegible]
[illegible]	Americium (Am)	[illegible]
	Cesium (Cs)	[illegible]
	Neptunium (Np)	[illegible]
	Plutonium (Pu)	[illegible]
	Strontium (Sr)	[illegible]
	Technetium (Tc)	[illegible]
	Uranium (U)	[illegible]
	Barium (Ba)	[illegible]
[illegible]	Americium (Am)	[illegible]
	Cesium (Cs)	[illegible]
	Neptunium (Np)	[illegible]
	Plutonium (Pu)	[illegible]
	Strontium (Sr)	[illegible]
	Technetium (Tc)	[illegible]
	Uranium (U)	[illegible]
	Barium (Ba)	[illegible]

[illegible] = no data available

zero (Table 5). Some radionuclides, including uranium and neptunium, are retarded by sorption values greater than 1 but less than 10 (Table 5).

For densely welded tuff with a density of about 2 g/ml and an effective matrix porosity of about 10%, radionuclide velocity will be on the order of 0.05 times the groundwater velocity for a Kd of 1. For a Kd of 100, the radionuclides will move about 5×10^{-4} times the velocity of water. For nonwelded tuff, radionuclide velocities will be about 0.2 and 0.002 times the velocity of water for Kd's of 1 and 100, respectively, assuming a density of 1.5 and a porosity of 30%.

Thick zones composed predominantly of zeolite minerals occur below the potential emplacement horizon in portions of the Calico Hills unit and the older tuff. Zeolites have abundant cations available for exchange plus a peculiar, open, crystal-lattice structure that allows access for waste species to regions deep within the lattice. Partly because of these peculiarities, zeolites have a greater capacity for sorption than many other minerals. Several waste elements have Kd's of more than 1000 in the Calico Hills unit (Table 5), so the rocks below the emplacement horizon may slow the velocity of cationic waste species moving with matrix-water flow by a factor of 20,000 or more relative to groundwater flow velocity.

For flow through fractures, less rock is in direct contact with moving water; hence, direct retardation by sorption is less effective than for flow through the matrix. A retardation factor for sorption in fracture flow is given by Burkholder (1976) whereby

$$Rd_i = 1 + AKa_i \tag{9}$$

where A is the ratio of surface area to void volume along fractures through which flow occurs, and Ka is an expression of Kd in terms of ml/cm^2 of reactive surface area. Assuming that fracture surfaces are smooth (i.e., have no roughness coefficient), A, conservatively, is equal to 2 divided by the width of the fracture, and the retardation factor for species i becomes

$$Rd_i = 1 + (2Ka_i/b) \tag{10}$$

where b is the fracture aperture width (Freeze and Cherry, 1979). This results in much less effective sorption for a given radionuclide in fracture flow than in matrix flow. For example, minerals along fracture surfaces would need Kd's of about 500 to retard radionuclide movement by a factor of only 2, assuming that Kd's from laboratory tests were calculated on the basis of 1 g of sorbing minerals possessing about 50 m^2 of surface area (Daniels et al., 1982) and that fracture apertures are about 10 μm wide (Table 3). Similarly, Kd's of 5000 and 50,000 would retard radionuclide movement in fractures by factors of about 10 and 100, respectively. If the apertures are narrower or wider, the retardation by direct sorption along the fractures would proportionally increase or decrease, respectively.

Effective retardation along fractures is likely to be much greater than actual retardation provided by sorption alone. The potential for diffusion of waste species along a concentration gradient into the rock matrix from solutions moving through fractures may significantly delay radionuclide movement (Neretnicks, 1980; Neretnicks et al., 1982; Rasmuson and Neretnicks, 1981; Walter, 1982; Grisak and Pickens, 1980). The generally high porosity of the tuffs at Yucca Mountain provides a large reservoir of storage space for waste species moving through fractures, even if the contaminated water in the fractures does not itself move into the rock matrix. Rather than a true retardation of radionuclide movement relative to fluid flow, this process will cause a transfer of waste mass from fluid in the fractures to fluid in the matrix. It will continue until the storage space in the matrix, determined by sorption equilibrium concentrations, is filled. Once in the matrix, the waste species will move with the porous water flow, subject to retardation by sorption. In effect, the radionuclides initially in the fractures are thereby "retarded" relative to fracture flow and fracture sorption.

In the tuffs at Yucca Mountain, this diffusion process will in all likelihood significantly compensate for rapid water flow and less effective sorption within fracture-flow systems. Diffusion will occur in the unsaturated zone under the unlikely case that the water flux exceeds the carrying capacity of the rock matrix and fracture flow occurs. Diffusion will also contribute to retardation in the saturated zone, where fracture flow is dominant under prevailing conditions. In the unsaturated zone, chemical diffusion due to concentration differences will be strongly accentuated by water advection along a hydraulic gradient as discussed in Section 3.1.3.1. The process also will significantly retard anionic or nonsorbing cationic species such as carbon, technetium, and iodine, thus strongly compensating for the lack of sorption of these species.

Diffusion into the rock matrix has been quantified for some rocks along the flow paths at Yucca Mountain (Travis et al., 1984). That study substantiates the conclusion that diffusion is potentially a significant mechanism for retarding the net movement of radionuclides relative to water-flow velocities in fractures. Travis and others show that diffusion may provide delay factors of several hundred for nonsorbing species and several thousand for sorbing species. In summary, ample evidence indicates that the geochemical conditions at Yucca Mountain will strongly inhibit the movement of radionuclides toward the accessible environment by both sorption and diffusion.

3.3 ROCK CHARACTERISTICS

The rock properties relevant for assessing repository behavior generally are related to the changes caused by repository development in the ability of the rock to transmit water toward and away from waste and the changes in water chemistry that might affect waste solubility. For the purposes of this report, these properties are restricted to the thermal and mechanical properties of the rock matrix and exclude existing structures such as fractures, faults, and stratigraphic features. These latter types of rock-mass features are addressed under geohydrology (Section 3.1) in the context of their effect on groundwater movement and its prediction. For this discussion the rock characteristics of primary concern are thermal conductivity, thermal expansion, and rock strength.

The vertical and lateral extent of rocks with properties amenable to accommodating the effects of repository construction and heat from the waste is another concern for rock characteristics. The variability of rock properties within a rock mass is an issue for siting only insofar as the range in properties exceeds some threshold of acceptability in terms of specific performance requirements. The greater the spatial extent of a rock mass with a set of properties within these thresholds, the greater will be the flexibility for relocating waste emplacement areas during design or construction should it become necessary to avoid some local, undesirable rock conditions. Mansure and Ortiz (1984) addressed this concern and concluded that considerable flexibility in the placement of waste is provided by the lateral extent of the host rock. We assume that emplacement will occur within the area outlined in Figure 1. Alternative options for the location of waste emplacement are not considered in this report, though there is no currently known reason to restrict waste emplacement to that area. It is further assumed that the thermal and mechanical properties of the host rock are relatively uniform throughout the emplacement area.

Current knowledge of the thermal and mechanical properties of the densely welded Topopah Spring Member indicate that the host rock will adjust to repository-induced perturbations without causing significant changes in isolation capabilities. The thermal conductivity of the host rock is about 2 W/m°C (Johnstone et al., 1984). This is sufficient to transmit heat from the waste rapidly enough to keep rock temperatures below 100°C a few meters to a few tens of meters away from the waste canisters for emplacement densities up to about 25 thermal W/m^2 (100 kW/acre) (Figure 9B) (Johnstone et al., 1984; Peters, 1983; Klasi et al., 1982; Johnson, 1982; Sundberg and Eaton, 1982). The actual emplacement density is expected to be much lower than 25 W/m^2 as indicated in assumption 3, Chapter 2 and evaluated for Figure 9A. Thus, in support of the assumption discussed in Section 3.2, the effects of repository heat on waste solubility, even at unrealistically high emplacement densities, are not expected to be significant after the containment period.

In the context of the natural stress environment at Yucca Mountain and the shear strength of densely welded tuff, additional stresses caused by thermal expansion should cause little or no new fracturing of the rock mass surrounding a repository. Shear movement along existing fractures should be limited to rocks within a few meters of the emplacement drifts (RE/SPEC, 1982; Johnstone et al., 1984).

Zeolite minerals, which occur in abundance in portions of the Calico Hills unit 50 m or more beneath the potential emplacement horizon, tend to dehydrate with increasing temperature. Temperatures in the highly zeolitic rocks are expected to peak at about 85°C 1000 yr after repository closure, thus always remaining below temperatures that would induce significant shrinkage of minerals and attendant changes in fracture apertures (Figure 10) (Johnstone et al., 1984; Klasi et al., 1982; Smyth, 1982). As a result, little or no change is expected in the hydrologic properties of the host rock or surrounding units due to fracturing from either construction of a repository or heat generated by radioactive decay of the waste.

Even if fracturing caused by heat were to occur, the changes probably would have negligible effects on water movement through the already fractured rocks in the unsaturated zone. This follows from the discussion in Section 3.1.3, where it was shown that the amount of water moving through fractures depends on the relation between the matrix hydraulic conductivity and total water flux. Neither the hydraulic conductivity, density, nor the location of fractures will greatly influence the partitioning of water flow between the rock matrix and the fractures; therefore, neither the amount nor the velocity of water reaching or leaving the repository should be noticeably affected by creation of new fractures or the opening or closing of existing fractures. For the portion of flux, if any, moving through fractures, flow velocities probably

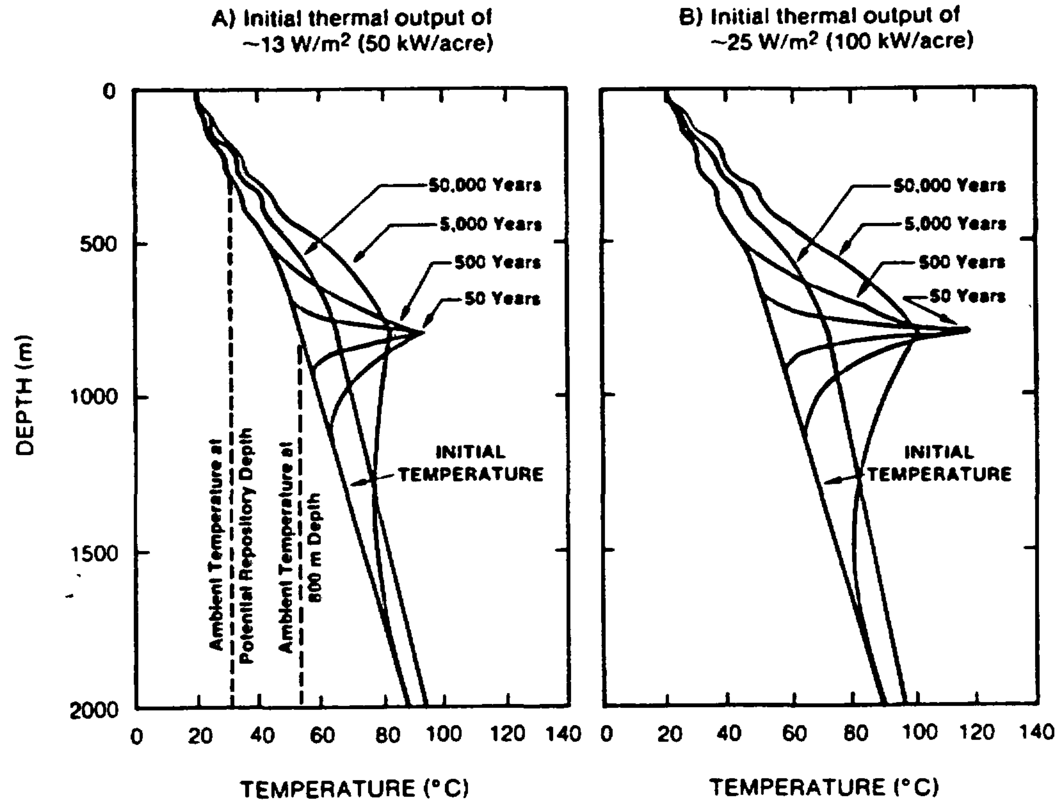


Figure 9. Vertical temperature profiles for a repository 800 m deep in densely welded tuff of the Bullfrog Member (see Table 2); ambient temperature at the current reference depth of about 350 m in the Topopah Spring Member is about 20 degrees C less than at depths assumed for the calculations (see Part A), so temperatures above and below a repository at 350 m would be about 20 degrees less than shown by the profiles (modified from Klasi et al., 1982).

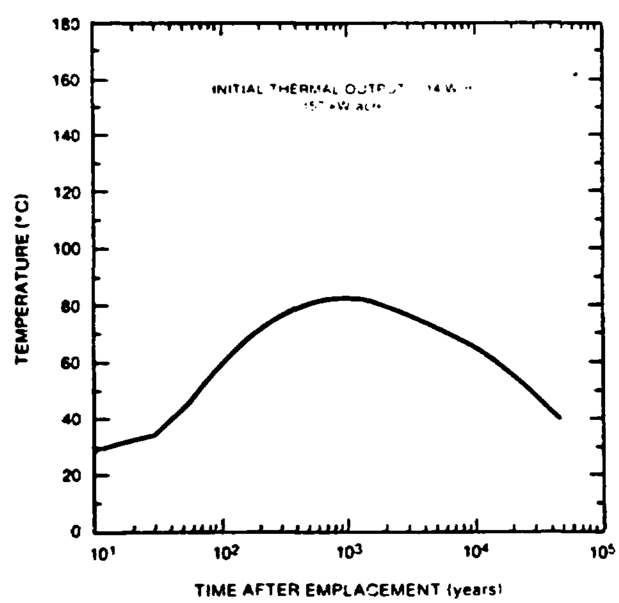


Figure 10. Temperature projections 50 m below a repository in the densely welded Topopah Spring Member (from Johnstone et al., 1984).

will be rapid because of low fracture porosity. Any changes in fracture apertures or density would tend to change effective fracture porosity. Depending on the number and size of fractures transmitting the water before the changes, such changes may or may not affect the velocity of water movement. Such changes, in any event, would occur only within a few tens of meters, at most, around the wastes and would have negligible effects on total flow time between the repository and the accessible environment.

The potential liberation of water under heating of mineral, especially zeolites that make up some of the tuffs of Yucca Mountain, may increase the volume of freely moving liquid water in rocks several meters from the waste. However, zeolites only occur tens of meters below the repository horizon where temperature increases and the associated amounts of liberated water are expected to be small. Near the waste, pore water would tend to be driven outward from the waste during the period of increasing temperatures (Pruess and Wang, 1983). During cooling, this water may migrate back toward the waste, eventually reestablishing the level of saturation that existed before waste emplacement. Thus, by the close of the containment period (300 to 1000 yr), the geochemical and hydrologic environments are expected to be similar to those now occurring. As a result, we do not explicitly account for potential changes in ambient conditions induced by repository activities for analyses of performance described in the following chapter.

CHAPTER 4. PERFORMANCE IN RELATION TO REGULATORY REQUIREMENTS

This chapter describes results of calculations of groundwater flow times, waste-dissolution rates, and releases of radionuclides at the accessible environment under a range of conditions for groundwater flux past the wastes in a repository at Yucca Mountain. The chapter is organized to address the distinct performance objectives of the NRC and the EPA. Groundwater flow time is addressed in Section 4.1 and compared to the NRC 1000-yr requirement. Section 4.2 addresses the ability of the site to comply with the NRC requirement for an annual release rate from the repository of less than 1 part in 100,000 of the curie content of individual radionuclides. Section 4.3 uses the release rates presented in Section 4.2 as a source term for calculations of radionuclide transport to the accessible environment by water movement as established in Section 4.1. Most transport calculations use only sorption as a geochemical-retardation mechanism. The results of transport calculations are discussed in terms of the EPA release limits.

All calculations were done by a computer program developed by J. P. Brannen and Y. T. Lin. The program has not been verified formally, but spot comparisons of its output with the results of manually performed analytical exercises have been made and show agreement. Description of the theoretical basis for the calculations is presented in Appendix A. The program is listed in Appendix B.

4.1 GROUNDWATER FLOW TIME

Analyses in this section address the NRC performance objective for the natural site; that is, the requirement for a prewaste emplacement, groundwater-travel time of 1000 yr from the disturbed zone around a repository to the accessible environment (NRC, 1983). Results from these analyses may also be interpreted to assess whether Yucca Mountain possesses the disqualifying condition for geohydrology listed in the DOE siting guidelines (DOE, 1983).

At this time, the boundaries of neither the disturbed zone nor the accessible environment are clearly defined. We assume that the disturbed zone extends downward from the repository no farther than the base of the densely welded portion of the Topopah Spring Member (including the vitrophyre which occurs near its base). The thickness beneath the repository of the disturbed zone defined in this manner is shown in Figure 11B and varies from more than 100 m in the east to just under 50 m in the west.

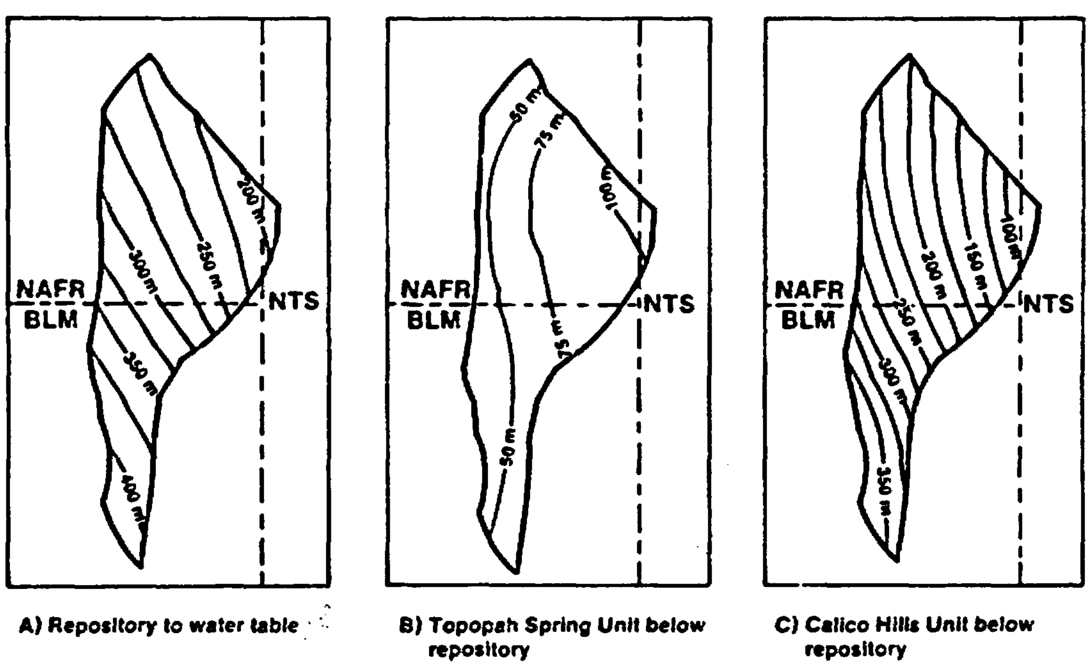


Figure 11. Contours of the thickness of unsaturated rock beneath the proposed repository area; Parts B and C represent component thicknesses of the total thickness shown in Part A (from IGIS, 1984)

As discussed in Section 3.3, temperatures at the edge of the disturbed zone where it has a minimum thickness of 50 m will reach a maximum of about 85°C about 1000 yr after emplacement of the waste. This compares to an ambient temperature of about 30° to 40°C at the base of the Topopah Spring Member. The NRC defines the disturbed zone as the region around a repository where changes caused by repository development would significantly affect radionuclide transport (NRC, 1983). Because no mechanisms have been identified that suggest how an increase in temperature from about 40° to 85°C or less would significantly alter the transport of radionuclides, particularly in the unsaturated zone, this definition of the disturbed-zone boundary provides a conservative basis for calculating groundwater travel times

We assume three cases for the definition of the accessible environment. All are based on definitions proposed by the EPA. The first case (Case A) is based on an unpublished working draft of 40 CFR 191 (EPA, 1984), which can be interpreted to require the accessible environment to include the saturated aquifer immediately beneath the repository. Though we believe this is an unnecessarily restrictive definition, considering the historical land-use control at the Nevada Test Site and more economical access to water supplies from the same aquifer in the basins immediately surrounding Yucca Mountain, we use it as a conservative case. *The flow path of concern for this case* is composed of only the vertical, unsaturated flow from the base of the densely welded tuff to the water table, i.e., flow through the unsaturated Calico Hills unit (Figure 3). In detail, the actual path to the aquifer underlying the host rock may include some vertical or inclined flow through some undetermined thickness of poorly transmissive rocks just below the water table or some inclined, tortuous, or locally lateral flow in the unsaturated zone. For simplicity, however, we conservatively assume for Case A that the water table (actually, the composite potentiometric surface observed as static water levels in wells) constitutes the accessible environment and coincides with the top of a horizontally flowing, unconfined aquifer in the saturated portion of the Calico Hills and older tuff units. The thickness of the unsaturated zone beneath the disturbed zone, as defined, varies throughout the Yucca Mountain site and generally exceeds 100 m (Figure 11, Part C). We assume the *flow path of concern for Case A* is composed of 100 m of the unsaturated Calico Hills unit. This is a conservative assumption because the 100-m thickness of unsaturated Calico Hills unit occurs where the thickest section, more than 100 m, of unsaturated Topopah Spring unit underlies the potential repository (Figure 11).

The second case for defining the accessible environment (Case B) is based also on the working draft of 40 CFR 191 (EPA, 1984). For this case the boundary of the accessible environment is assumed to occur 2 km in a horizontal direction from the waste-emplacement area. For our analyses we interpret this to mean that the accessible environment occurs in the saturated zone at the end of a 2-km flow path. *The flow path of concern for this case* is composed of vertical flow to the water table, described for Case A, plus 2 km of horizontal flow in the saturated zone (Figure 3). Assuming that the 2 km of horizontal distance corresponds to 2 km of flow path means that we take no credit for tortuous saturated flow.

The third case (Case C) is based on the published, proposed version of 40 CFR 191 (EPA, 1982). This case assumes the accessible environment is located 10 km horizontally from the waste emplacement area. We treat the distinction between Cases B and C by assigning a 200-yr flow time in the saturated zone to Case B and a 2000-yr flow time to Case C. Though the different flow times in the saturated zone for Cases B and C are generally intended to address alternative definitions of the accessible environment, they also may be interpreted to encompass uncertainty in flow time for a path of fixed length caused by uncertainty about hydraulic conductivity and effective porosity.

Results of groundwater travel-time calculations for all three cases and for the most likely flux of less than 1 mm/yr through the unsaturated zone are shown in Figure 12. Calculations of flow time solely through the unsaturated zone (Figure 12, Case A) are based on Equation 1 in Section 3.1.3. An effective porosity of 0.1 was used to provide a conservative basis for flow velocity through the matrix material of the zeolitic Calico Hills unit. Flow time is obtained simply by dividing the velocity by the flow distance of 100 m. As pointed out in Section 3.1.2, flux through the unsaturated zone probably is limited to a value equal to the hydraulic conductivity under observed moisture tensions of more than 20,000 cm. We assume the unsaturated conductivity is equal to the flux because the gradient is 1. Therefore, values for flux used for the unsaturated part of the flow path (Figure 12, Case A) may be conservative for values greater than a few tenths of a millimeter per year. If the flux, as expected (see Section 3.1.2), is less than 0.5 mm/yr, unsaturated-flow time will exceed 20,000 yr; it will exceed hundreds of thousands of years if the flux is less than about 0.1 mm/yr (Figure 12). Under expected conditions, then, flow time is well in excess

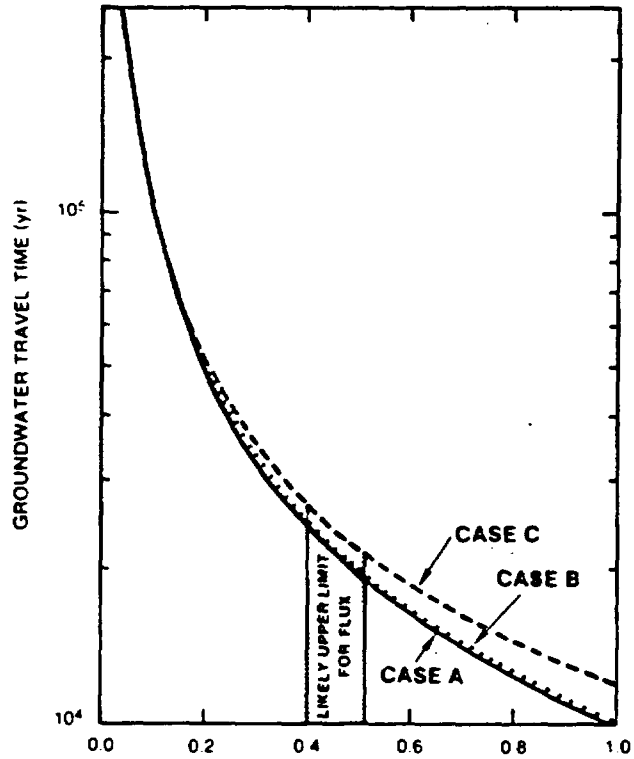


Figure 12. Fastest groundwater flow times from the disturbed zone to the water table (Case A), to the end of a 200-yr saturated flow path (Case B), and to the end of a 2000-yr saturated flow path (Case C); all cases based on a likely flux through the unsaturated zone of less than 1 mm/yr.

of the 1000-yr requirement, even if the accessible environment occurs at the water table immediately beneath the repository (Figure 12, Case A).

For all conditions of flux through the unsaturated zone, flow time in the saturated zone is assumed to be a constant of either 200 yr (Case B) or 2000 yr (Case C). Flow time in the saturated zone, Ts, was determined by considering the site properties expressed by the equation:

$$T_s = D\left(\frac{Ki}{n}\right)^{-1} \qquad (11)$$

where D is a flow distance of 10 km; K is the saturated hydraulic conductivity of either 30 or 300 m/yr and represents alternative bulk-rock-mass conductivities; i is the hydraulic gradient of 0.00034; and n is an effective fracture porosity of 0.002. The saturated flow times used for generating Figure 12, 200 or 2,000 yr, are similar to the values of 196 and 1961 yr calculated using Equation 11. They were simply added to the unsaturated flow time for Case A to obtain total flow time to an accessible environment 2 or 10 km away from the repository (Figure 12, Cases B and C, respectively).

The scale of the plot in Figure 12 does not allow much discrimination between Cases A and C, or especially Cases A and B, so total flow times for Cases B and C are essentially the same as for Case A. Accordingly, total flow time to an accessible environment 2 or 10 km away from the repository (Cases B or C) would be dominated by flow to the water table under expected conditions of flux through the unsaturated zone. Uncertainty about the total flow time is not sensitive to either definition of the accessible environment or to uncertainty about saturated flow conditions (Cases B and C).

Figure 13 shows groundwater travel times for the unlikely event that flux through the unsaturated zone exceeds 1 mm/yr. In this event, the flux would exceed the hydraulic conductivity of the matrix of the zeolitic Calico Hills unit, and this unit would be unable to pass all the water through matrix pores. The water in excess of about 1 mm/yr would be diverted horizontally through material with a horizontal conductivity corresponding to the excess flux until it encountered a zone, assumed to be a fracture, where the vertical conductivity is sufficient to pass the excess flux vertically to the water table. The vitric Calico Hills unit is able to vertically transmit all unsaturated flux up to several hundred millimeters per year through the matrix, so flow times from portions of the repository above the vitric unit would remain more than 10,000 yr even if flux exceeded 1 mm/yr. To move vertically through the zeolitic Calico Hills unit, water in excess of about 1 mm/yr would have to move down fractures with effective porosities much lower than the matrix (assumed for calculations to be 0.001 compared to 0.1 for the matrix). Flow time would be reduced correspondingly. The effects of this unlikely condition are shown in Figure 13 where the travel times for flux of up to 20 mm/yr are plotted.

Figure 13 indicates that groundwater flow time to the accessible environment is very sensitive to whether flux through the unsaturated zone can be transmitted by the matrix or whether it must move through fractures. If some flow in the unsaturated zone is entirely through fractures, flow time along the fastest path to the accessible environment, i.e., through the zeolitic Calico Hills unit, would be dominated by saturated flow (Figure 13, Cases B and C). In this event, the accessible environment would have to occur several kilometers, perhaps the full 10 km, horizontally from the repository for the site to meet the 1000-yr flow-time requirement. As flux through

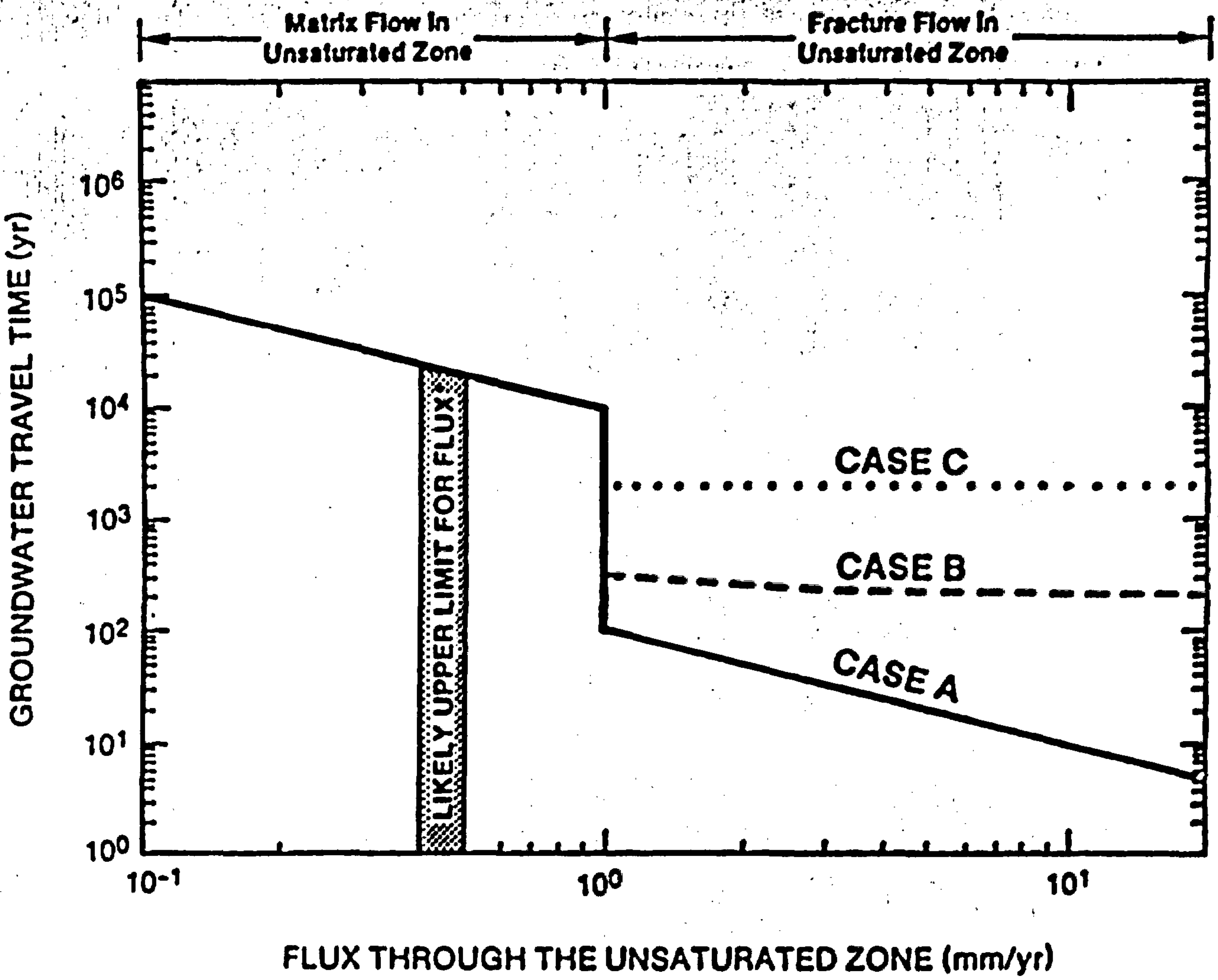


Figure 13. Groundwater flow times for Cases A, B, and C (see text) under unlikely conditions of flux up to 20 mm/yr, abrupt change in flow times at a flux of 1 mm/yr corresponds to a transition in the unsaturated zone between flow entirely in the matrix pores and flow in both fractures and matrix pores: flux greater than 1 mm/yr yields much shorter flow times through fractures in the unsaturated zone accounting for the abrupt change

the unsaturated zone increases, total flow time approaches flow time for the saturated zone alone. Accordingly, the value of effective hydraulic conductivity in the saturated zone is a major source of uncertainty about the total flow time if flux in the unsaturated zone exceeds the hydraulic conductivity of the matrix (compare Cases B and C, Figure 13).

In summary, it appears that the Yucca Mountain site easily satisfies the NRC and DOE requirements for a 1000-yr groundwater flow time to the accessible environment under the most likely conditions of flux through the unsaturated zone. This is true whether the accessible environment were to occur at the water table or at the end of either a 2- or 10-km flow path in the saturated zone, because flow time is likely to be dominated by slow percolation of water through the rock matrix in the unsaturated zone. Under unlikely conditions of unsaturated flux of more than about 1 mm/yr, flow time through the saturated zone would be the major component of total flow time.

The 1 mm/yr value for flux, above which significant fracture flow would occur, generally corresponds to the saturated hydraulic conductivity of the Topopah Spring and zeolitic Calico Hills units. Because the actual transition value varies within each unit and among different units, intervals of local fracture flow may be interspersed with intervals of local matrix flow. More widely distributed data are needed on both the vertical and the horizontal components of both saturated and unsaturated effective hydraulic conductivity of the rock matrix to allow more accurate characterization of this transition value throughout the unsaturated zone at Yucca Mountain.

4.2 WASTE-DISSOLUTION RATE

The performance objective addressed in this section is the limit on annual releases of waste from the engineered barrier system. The NRC codified this objective by setting a limit on predicted releases of 1 part in 100,000 of the inventory of each radionuclide constituting at least 0.1% of the total waste inventory calculated to be present 1000 yr after closure of the repository (Table 1). The engineered barrier system is defined by the NRC to include the waste package and the underground repository facilities (NRC, 1983).

Barriers to releases will be provided by waste packages and, for spent fuel, will include the uranium oxide itself, zircaloy cladding, stainless steel canisters necessary for waste handling, and any specially designed materials placed between the canisters and the emplacement holes in the rock. For disposal in the unsaturated zone, such packing materials might be designed to include air gaps that will inhibit by capillary processes the movement of water toward and away from the waste (Fernandez and Freshly, 1984; Winograd, 1981; Herzog et al., 1982; Roseboom, 1983). Artificial drainage channels might be designed within the underground facility to divert flowing water away from waste-emplacement areas (Roseboom, 1983). Other designed barriers might include some volume of rock around the waste packages and emplacement drifts. This volume will most likely be determined by a planned zone of sufficient heating and commensurate drying of the rock to cause moisture gradients that inhibit movement of liquid water toward the wastes (Pruess and Wang, 1983; Evans and Huang, 1983; Roseboom, 1983).

Compliance with the NRC's release limits will eventually be assessed by giving proper consideration to engineered barriers. The design details of these barriers are not available, so we cannot establish the outer boundaries of the engineered-barrier system or the expected behavior within these boundaries. This leads us to adopt a conservative approach whereby no engineered barriers are assumed to be in effect and releases from the engineered-barrier system are controlled solely by the natural features of the site and the solubility of uranium, which constitutes most of the spent fuel.

Release rates are determined for this report by assuming that some part of the water intercepting the waste-emplacement area will contact the spent fuel and become saturated with uranium. We assume three cases for determining that amount of water:

1. All water flowing vertically to an area defined by the cross-sectional area of vertical emplacement holes will interact with the waste. This case is based on emplacement of 35,000 canisters about 65 cm in diameter in 35,000 holes 100 cm in diameter drilled into the floors of emplacement drifts. It leads to an assumption that 0.25% of the total flux passing through the repository level will interact with the waste. This case is slightly conservative in that 35,000 holes 100 cm in diameter would occupy somewhat less than 0.2% of the total repository area of about 6×10^6 m^2.
2. All water flowing vertically to an area defined by the cross-sectional area of horizontal emplacement holes will interact with the waste. This case is predicated on emplacement of multiple canisters in long, horizontal boreholes drilled into the walls of mined tunnels. It leads to an assumption that 2.5% of the total flux will interact with the waste. This percentage is also slightly conservative because a typical canister for spent fuel is 300 cm long, yielding a total intercept area of 105,000 m^2 for 35,000 canisters placed in holes 100 cm in diameter. Compared to a total repository area of about 6×10^6 m^2, this means that about 1.75% of the vertically moving flux would intercept the emplacement holes. Even if emplacement holes were twice as wide as the canisters (Jackson et al., 1984), only about 2.3% of the water flux would intercept the emplacement area.
3. All water flowing vertically to the area of mined openings will interact with the waste, a very conservative assumption in that some mechanism, currently unforeseen, would be required to concentrate flow as it moves through the repository. According to current information, quite the opposite would probably happen. Openings created by the repository, even if backfilled, would tend to act as capillary barriers, thus diverting flux away from, rather than into, excavated areas (Fernandez and Freshly, 1984). This case conservatively assumes that mining of repository drifts will remove about 25% of the rock at the level of the underground facilities. Thus, the total amount of water available to dissolve waste for this case is assumed to be 25% of the total flux passing through the repository horizon.

Simply, the three cases used for calculations are that 0.25%, 2.5%, or 25% of the water flowing through the repository level will interact with the waste. All three cases require some mechanism, as yet undiscovered, that would allow liquid water in the unsaturated zone to pass through voids in the waste emplacement holes so that contact with the waste canisters could occur. Thus, all three cases provide a highly conservative basis for estimating potential releases from the engineered-barrier system.

As outlined in Chapter 2, assumption 8, and described in Section 3.2.1, we assume that releases into the water are controlled solely by the solubility of uranium, which as an oxide makes up the matrix of the waste. We used a value for uranium solubility of 4×10^{-4} kg/m^3 of water to encompass current uncertainty about the actual value in the oxidizing environment that will exist near the wastes (see Section 3.2.1). The presence of zircaloy cladding, steel canisters, and packing materials may lower the Eh of water actually contacting the waste, resulting in lower solubilities. Because dissolution rates are assumed to be directly proportional to both uranium solubility and the amount of water contacting the waste, the three cases listed above for determining this amount may be construed also to represent three cases of uranium solubility for a given volume of interacting water. For example, if 2.5% of the total flux were to contact the waste, Case 1 would represent a uranium solubility of 4×10^{-5} kg/m^3; Case 2, 4×10^{-4} kg/m^3; and Case 3, 4×10^{-3} kg/m^3.

The cladding and canister materials will tend to delay the penetration of corrosive surfaces to the waste itself, perhaps for thousands to tens of thousands of years in the low flux environment at Yucca Mountain (Oversby, 1983, McCright et al., 1983; Wilson and Oversby, 1984). Other waste-package components, such as air gaps, will inhibit contact of incoming water with the waste as well as inhibit movement of water carrying dissolved radionuclides away from the waste. Lower effective solubilities than we assume in this report are likely because of these engineered features as well as kinetic factors such as the development of weathering rinds around the unaltered spent fuel and rate-limited dissolution in droplets of water that may quickly run along the surface of the waste form. In addition, solubilities of many waste species, such as americium and plutonium, are less than for uranium (Kerrisk, 1984). Unless considerable separation of waste species from the fuel matrix has occurred, species with solubilities higher than uranium probably will not be released to solution until the uranium matrix dissolves enough to allow water contact with individual particles of these species (Braithwaite, 1984). The rate of dissolution of uranium thus constrains the individual dissolution rates of these species, assuming they are not significantly concentrated on exposed surfaces of the spent fuel.

Though we cannot precisely identify the actual conditions that will occur at the water-waste contact, these conditions should tend to slow dissolution rates relative to those determined solely by the solubility of uranium. By allowing water to overcome capillary barriers and begin dissolving the wastes and by assuming releases are based on a high solubility for uranium, we are being highly conservative, perhaps to the point of seriously overestimating waste dissolution in a repository at Yucca Mountain. However, such an approach can point to the unique qualities of the site, independent of engineered features, which will contribute to waste containment.

Results of our calculations for expected flux through the unsaturated zone of less than 1 mm/yr are shown in Figures 14 and 15. Figure 14 shows the

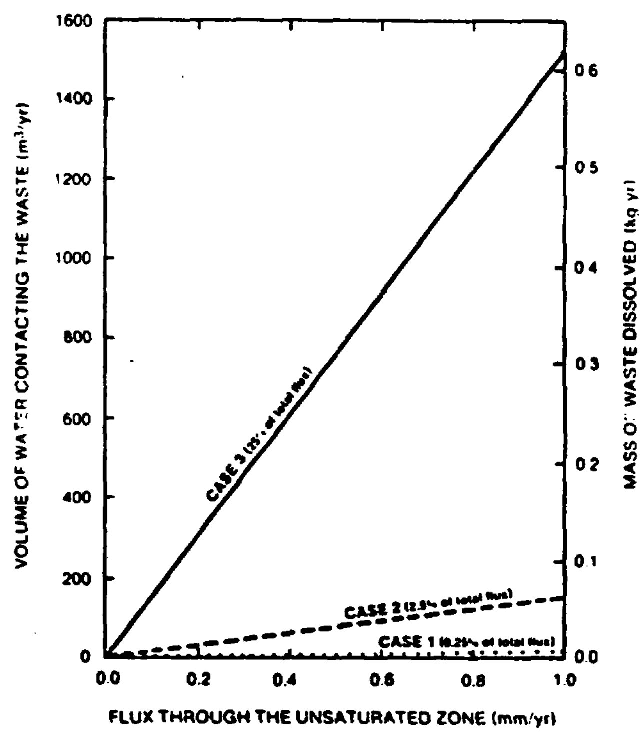


Figure 14. Annual volume of water contacting all of the waste in the repository and the corresponding total amount of waste dissolved for a uranium solubility of 4×10^{-4} kg/m^3 of water as a function of flux up to 1 mm/yr through the unsaturated zone; Cases 1, 2, and 3 represent different amounts of total flux interacting with the waste (see text); the three cases also may be interpreted to represent order-of-magnitude variations in uranium solubility for a single amount of interacting water.

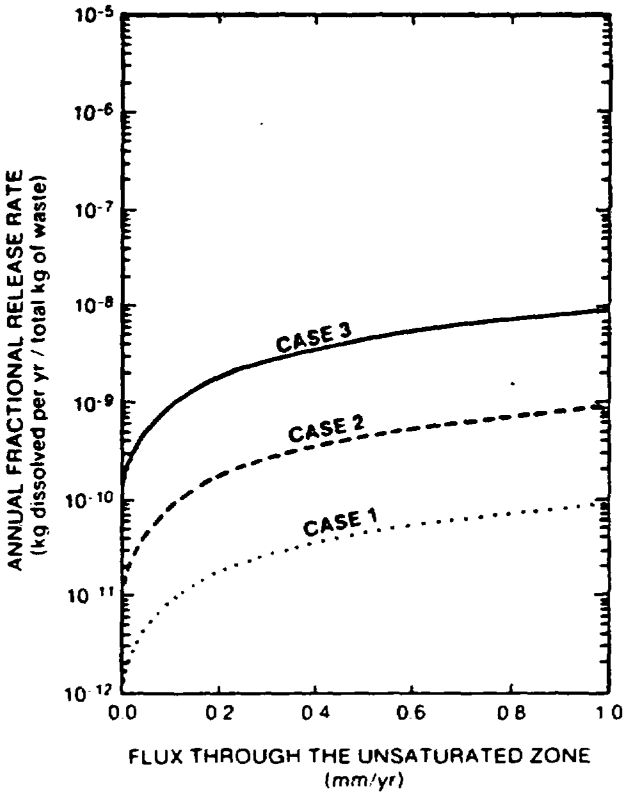


Figure 15. Annual mass-fraction of radionuclides dissolved at the repository by flux through the unsaturated zone of less than 1 mm/yr. Cases 1, 2, and 3 represent different amounts of the total flux interacting with the wastes (see text).

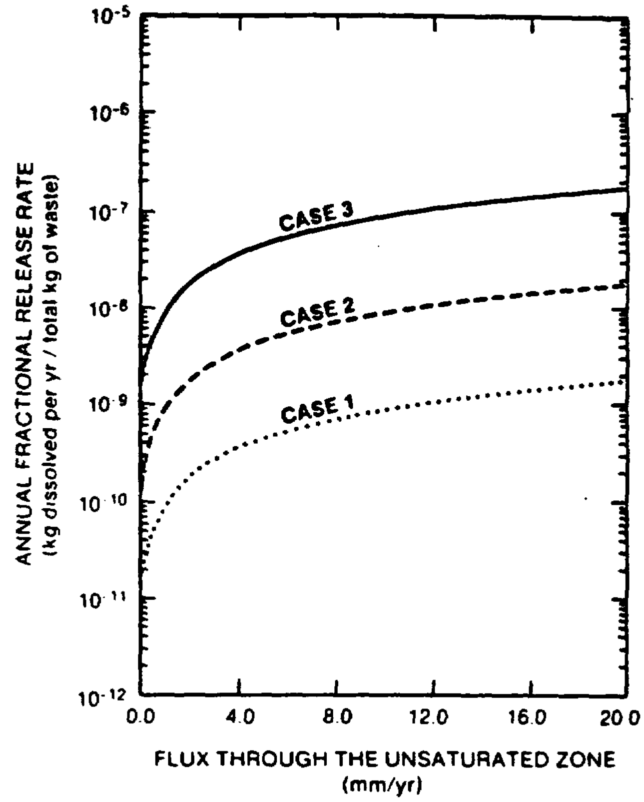


Figure 16. Annual mass-fraction of radionuclides dissolved at the repository by flux of up to 20 mm/yr; Cases 1, 2, and 3 represent different amounts of the total flux interacting with the wastes (see text).

annual volume of water contacting the waste and the corresponding mass of dissolved waste for the three cases of presumed contact area. Figure 15 shows the ratio of the annually dissolved mass to the total mass of waste in the spent fuel. This ratio is nearly constant in time and does not significantly depend on the period of complete containment. Figure 15 indicates that annual releases will constitute only about 1 part in 10^8 of the total mass of the spent fuel, even under the highly conservative case where 25% of a total flux of 1 mm/yr is assumed to interact with the waste. For unlikely flux values up to 20 mm/yr, which encompass and probably exceed credible amounts of flowing water that might be caused by climatic changes, the annual mass releases would still be less than 1 part in 10^6 (Figure 16).

Annual release rates, in terms of mass fraction, R, were calculated from

$$R = \frac{q \cdot s_u}{m_u(t)} \cdot G(t) \quad \text{(kg/yr)} \qquad (12)$$

where q is the annual volume of water contacting the wastes in m^3, s_u is the solubility of uranium in kg/m^3, $m_u(t)$ is the total mass in kg of uranium in spent fuel at time t, and G(t) is a function representing the history of containment. Assuming congruent leaching, the fractional release of mass for individual radionuclides is the same as for uranium (see Equations 10 through 14, Appendix A). Because the mass of uranium is dominated by U-238 with a half-life of nearly 5 billion years, the fractional release rate is essentially constant in time, assuming q and s_u are constant and G(t) equals 1. This constancy holds only when q times s_u is very small compared to $m_u(t)$, so mass loss of $m_u(t)$ is negligible over the time period of concern. Because uranium mass in the spent fuel is essentially constant for the flux and uranium solubility used in our calculations, any arbitrary total mass of the spent fuel, as a function of time less than about 1,000,000 yr, yields essentially the same fractional release rate. We arbitrarily chose uranium mass at 10 yr after removal from the reactors (t = 10 yr from Table 1) to calculate fractional releases.

Figure 17 expresses the mass-dissolution rates another way. In this figure the total time required to dissolve all spent fuel in a repository is plotted for the likely range of flux, i.e., up to 1 mm/yr. This figure suggests that billions of years would be required to dissolve all the waste in a repository if current conditions prevailed. Of course, site conditions will change, perhaps dramatically, over such long times, and the wastes will have decayed to insignificant levels of radioactivity. The predicted total leach times are shown only to indicate the very slow releases expected during the next tens to hundreds of thousands or perhaps millions of years during which conditions will probably remain grossly similar to those occurring today

Release rates shown in Figures 14 through 17 are based implicitly on an assumption that all waste packages fail instantaneously, simultaneously, and completely, i.e., release wastes to the limit set by uranium solubility. This is represented mathematically by assigning a value of 1 to G(t) in Equation 12. A more realistic scenario is that most packages will completely contain all wastes for a given time but a few will have slight flaws that allow small amounts of waste to escape as soon as water contacts the canisters. As time progresses, more packages are likely to fail (i.e., begin releasing their contents) until the maximum rate, determined by uranium solubility, is reached. This process of progressively decaying containment may be represented by G(t) in Equation 12, describing a constant failure rate that is the reciprocal of the time during which 63% of the canisters have failed, referred to as the mean time-to-failure. The corresponding release rate would be proportional to a cumulative distribution in time (see Appendix A, Equation 9). Because we do not know the proper description of waste-package performance, we chose a simple exponential distribution with a mean time-to-failure of 10,000 yr, a conservative time required to corrode the stainless steel canisters and zircaloy cladding that will surround and protect the spent-fuel matrix.

Figure 18 compares the trends of fractional release rates of waste mass for progressively decaying waste packages and for waste packages that are 100% effective until complete failure 300 or 1000 yr after

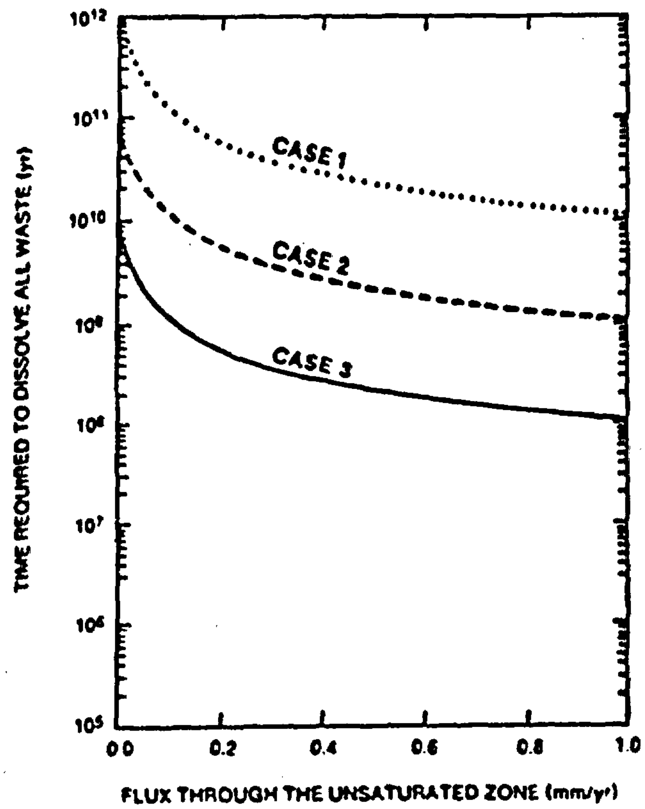


Figure 17. Total time required to dissolve all waste in a repository at Yucca Mountain if current conditions prevail; Cases 1, 2, and 3 represent different amounts of the total flux interacting with the wastes (see text)

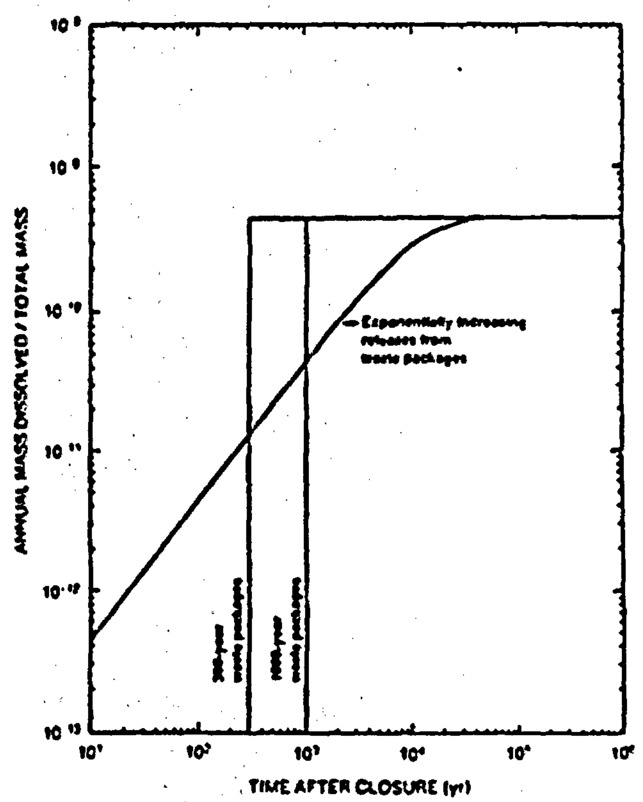


Figure 18. Annual mass-fraction of waste dissolved as a function of time by 2.5% of a total flux of 0.5 mm/yr for 300- and 1000-yr waste packages and packages with an exponentially increasing loss of containment.

repository closure. Though all radionuclides will begin to dissolve earlier than for waste packages that achieve complete containment for 300 or 1000 yr, the early mass releases caused by progressive failure will be negligible because of the initial limited failure rate. If complete containment for 300 or 1000 yr were achieved in conjunction with subsequent progressive failure, initial mass releases might be limited to a few percent of releases from instantaneously failing packages (Figure 18). Mass releases would then remain lower until several tens of thousands of years after closure, when they finally would converge with release rates determined solely by uranium solubility. In short, progressively decaying waste packages may allow releases to begin sooner but will limit them to levels well below those based on either 300- or 1000-yr waste packages for several decamillenia.

The concept of progressive waste-package decay is based on understanding of the likely site conditions at Yucca Mountain and does not rely on any special engineered features other than those that already exist, i.e., zircaloy cladding, or are necessary to handle and emplace the waste in a repository, i.e., a steel canister. The behavior of these materials in the low flux through the repository will probably restrict releases from the waste packages to some kind of distribution, such as the assumed exponential distribution. The exact form of the leaching model for Yucca Mountain remains to be determined.

We adopted an approach for Figure 18 that assumed some canisters would partially fail immediately after repository closure. This approach is likely to overestimate early releases because the thermal field around the wastes may prohibit flow away from the emplacement holes for several hundred years. In addition, voids within the emplacement holes will probably act as effective capillary barriers that will prohibit water from moving from the rock to the waste canisters. As a result, Figure 18 is not intended as a projection of actual releases stemming from an actual set of waste packages that will be emplaced at Yucca Mountain. Rather, the purpose of Figure 18 is to point out that the expected releases from the repository will probably be less than indicated by adopting an unrealistic assumption that all waste packages fail completely and simultaneously either 300 or 1000 yr after repository closure. The likely corrosion rate of canisters in the low flux at Yucca Mountain makes such failure modes highly unrealistic.

Figures 14 through 18 show annual fractional releases of the total mass of the waste in spent fuel and cannot be compared directly to the NRC release-rate limits, which are expressed in terms of curies. To compare annual curie release rates to the NRC limits, the annual mass releases in kg/yr of individual radionuclides must be multiplied by the specific activity expressed as Ci/kg. This number, in Ci/yr, can then be divided by the NRC release-rate limit for each radionuclide given in Table 1 to assess how well the Yucca Mountain site is expected to comply with the NRC requirements.

Figure 19 shows curie release rates for individual radionuclides and the integrated rate for all radionuclides normalized so that the NRC limits are set to equal 1. This figure is based on an unrealistic assumption that waste dissolution begins immediately after closure of the repository and continues unabated except by the solubility of uranium and the volume of water contacting the waste. Two-and-one-half percent of a total flux of 0.5 mm/yr is assumed to react with the waste. The releases shown on Figure 19 are unrealistically conservative during the early times when releases of short-lived cesium and strontium would be near the NRC release limits. By 300 yr after closure, a conservative initial time for any releases, these fission products would be reduced by radioactive decay to the extent that they would be released at only one thousandth of the release-rate

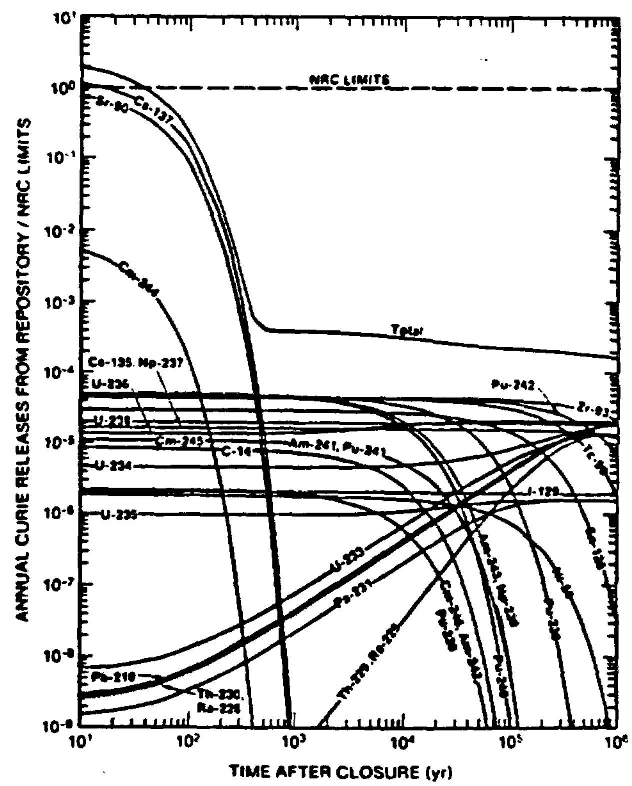


Figure 19. Ratio of the NRC release-rate limits of curies dissolved at the repository by 2.5% of a total flux of 0.5 mm/yr; release ratios shown for individual radionuclides (lower curves) and all radionuclides in combination (upper curve).

limit. Curium-244 also would be released at relatively high rates during the first 100 yr after closure, assuming no containment, because of its high specific activity. In combination, these three radionuclides would dominate the early total releases shown by the upper curve on Figure 19 if no containment period were in effect.

After about 400 yr, total release rates would remain nearly constant for at least 1 million yr, indicating the negligible effect that complete containment for an arbitrary period longer than about 400 yr would have on eventual release rates. The longer-term, nearly constant total release rate, about one thousandth of the sum of the NRC limits for individual radionuclides, would be dominated for about 10,000 yr by long-lived isotopes of carbon, cesium, technetium, zirconium, tin, plutonium, uranium, americium, neptunium, and curium. Each of these elements would contribute more than 1% to the total release rate vis-a-vis the NRC limits. Release rates of several nuclides, including C-14, Pu-239, Pu-240, Pu-242, Cm-245, Am-241, Am-243, and Cm-246, would decay to negligible levels during the first 100,000 yr following closure, whereas release rates of U-233, Ra-225, Ra-226, Pb-210, and Th-229 would increase to more than 1% of the total by 1 million yr after closure. Several nuclides, including Ni-59, I-129, U-235, and Pu-242 would never exceed more than about 0.1% of the total release rate. In no case would the release rate of a single radionuclide exceed one ten-thousandth of the NRC limit during the first million years. The relatively large releases of zirconium, plutonium, and americium nuclides shown on Figure 19 probably overstate likely releases, because these elements will probably be much less soluble than uranium in a repository environment at Yucca Mountain (Kerrisk, 1984). Our assumption that they will leach congruently with uranium results in projected releases that do not account for their low solubilities.

The ratio of total-curie releases to the sum of the NRC limits for individual nuclides is shown in the upper curve of Figure 19. Figure 20 compares this measure for 300-yr, 1000-yr, and exponentially decaying waste packages. Any of these forms of waste package behavior would limit the initial high release rates indicated on Figure 19 to levels well below the NRC limits by prohibiting or inhibiting releases of short-lived nuclides.

Yet another way to express expected performance at the repository is shown in Figure 21. This figure plots a three-dimensional representation of the ratio of cumulative curies dissolved and remaining in solution at any given time to the EPA release limits as a function of the likely range of flux through the unsat-

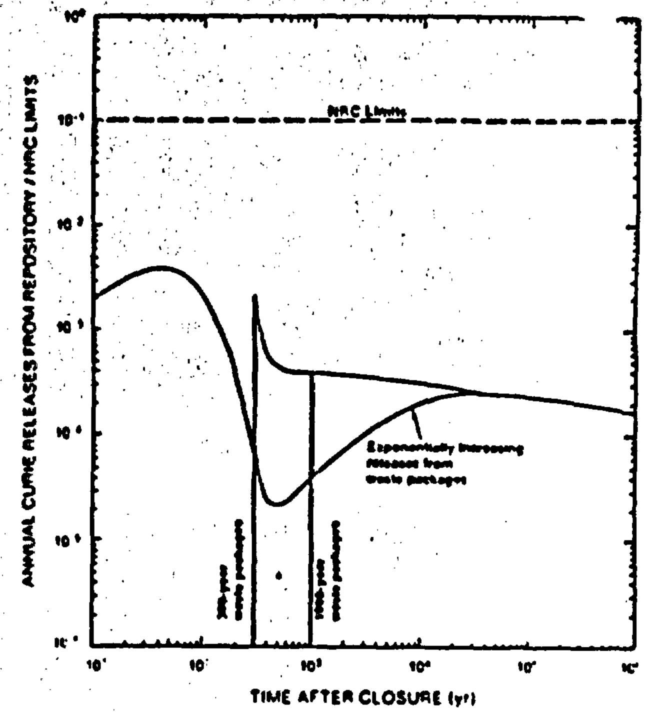


Figure 20. Ratio of the sum of NRC release rate limits for individual radionuclides of total curies dissolved at the repository by 2.5% of a total flux of 0.5 mm/yr for 300- and 1000-yr waste packages and packages with an exponentially increasing loss of containment.

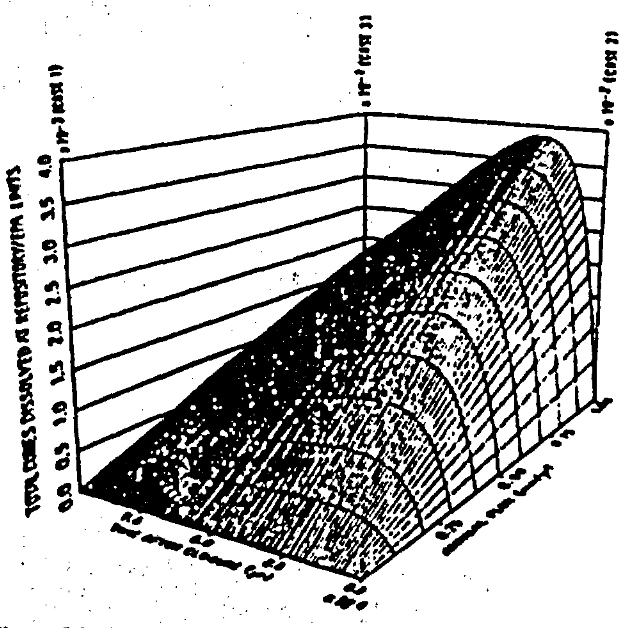


Figure 21. Ratio to the EPA limits of total curies dissolved at the repository by a total flux of up to 1 mm/yr; three cases for different amounts of the total flux contacting the waste are represented by the three vertical axes of the graph (left vertical axis for Case 1 or 0.25% of the total flux, right axis for Case 2 or 2.5%, and rear axis for Case 3 or 25%); plot assumes complete containment for 300 yr and accounts for the decay of radioactivity after the wastes have dissolved.

urated zone. For more likely cases where 0.25 or 2.5% of the total flux would contact the waste (see left and right axes, respectively, on Figure 21), the total curies outside the waste packages at any point in time would remain less than a few percent to a few tenths of a percent of the proposed EPA release limits. For flux less than 1 mm/yr and complete containment for 300 yr (the basis for Figure 21), total curies remaining in solution will never exceed the EPA cumulative release limits, even if 25% of the total flux interacts with the wastes (rear axis, Figure 21). Figure 21 indicates that low flux through the unsaturated zone at Yucca Mountain will ensure slow enough waste dissolution that compliance with the EPA standard would probably occur even if the standard were applied at the repository itself.

In summary, it appears that even without engineered barriers a repository at Yucca Mountain would easily comply with the NRC requirements for slow releases of wastes from the engineered-barrier system. If engineered barriers were considered, including specially placed capillary barriers, steel canisters, zircaloy cladding, repository drainage systems, and heat-induced moisture gradients, only an insignificant amount of water, or no water at all, would contact the waste. Actual release rates, therefore, are likely to be negligible. Simply, the amount of water flowing at Yucca Mountain is so low that release rates, in all likelihood, will be very slow and well within the limits set by the NRC.

4.3 RELEASES TO THE ACCESSIBLE ENVIRONMENT

The EPA will provide the environmental standards against which predictions of repository performance ultimately will be judged. The current proposed standards limit the total curies that may be released to the accessible environment during the next 10,000 yr, as discussed in Section 1.2 (EPA, 1982; 1984). The allowable releases are expressed in curies per 1000 MTHM (Table 1).

To address these standards we assumed that all waste dissolved at the repository, as established in Section 4.2, is transported from the disturbed zone toward the accessible environment by groundwater moving at rates established in Section 4.1. Flow within the disturbed zone is also considered, consistent with the EPA proposed regulations, which do not recognize a distinction based on the disturbed zone. Optional locations of the accessible environment are assumed to be the same as defined for groundwater travel time, i.e., at the water table and at the end of 200- and 2000-yr flow paths in the saturated zone. Geochemical retardation is assumed to slow radionuclide movement relative to groundwater flow according to the principles discussed in Section 3.2.2.

The values of retardation used for individual radionuclides are shown in Table 6. These values were applied to all rock types occurring along two flow paths through the unsaturated zone considered in our analyses (Figure 3). Matrix retardation was used for all portions of flow paths through the vitric part of the Calico Hills unit for all conditions of flux, and through the zeolitic Calico Hills unit for flux less than 1 mm/yr, the likely threshold value for matrix flow. For flux greater than 1 mm/yr, fracture retardation was used along all portions of the flow path passing through the zeolitic Calico Hills unit. The matrix values on Table 6 generally correspond to the lowest sorption value listed on Table 5 for rock types occurring along the flow paths of interest; the fracture values were calculated from the lowest sorption values. This procedure provides a simple, but conservative, basis for calculating radionuclide transport through the rocks at Yucca Mountain.

4.3.1 Bounded Releases to the Water Table under Expected Site Conditions

Figure 22 shows the calculated ratio of curies released at the water table during the next 100,000 yr to the EPA's release standards for flux up to 1 mm/yr. This figure indicates that no releases to the accessible environment should occur during the 10,000-yr period of compliance with the EPA standard, even if the accessible environment occurs at the water table directly below the repository. A reasonable upper limit on flux of 0.5 mm/yr (see Section 3.1.2) is highlighted on Figure 22. Figure 23 shows cumulative releases from the repository (upper line) and to the water table (lower lines) for this flux, including the contributions of individual radionuclides to releases at the water table. The area between the upper curve and lower set of curves on Figure 23 represents the isolation potential provided by the unsaturated zone.

For 0.5 mm/yr flux, groundwater travel time from the disturbed zone to the water table will be about 20,000 yr (Figure 12). It follows that no radionuclides would reach the water table for about 30,000 yr after closure of the repository (Figures 22 and 23). The additional 10,000 yr represents a 300-yr period of complete containment within the waste packages and, more significantly, groundwater travel time from the repository to the edge of the disturbed zone. The disturbed zone is defined as in Section 4.1 to occur at the base of the vitrophyre about 50 to 100 m below the proposed repository level (Figure 11).

Table 6. Sorption values of radionuclides in tuff matrix, Kd, and fractures, Ka, and corresponding retardation factors, Rd, used for calculations of radionuclide movement relative to groundwater flow.

Element	Kd (cm^3/g)(1)	Ka (g/cm^2)(4)	Rd for Matrix Zeolitic(5)	Vitric(6)	Rd for Fractures Unsaturated(7)	Saturated(8)
Am	180	1.8×10^{-4}	3600	1800	1.4	1.0
C	0	0	1	1	1.0	1.0
Cm	180	1.8×10^{-4}	3600	1800	1.4	1.0
Cs	290	2.9×10^{-4}	5800	2900	1.5	1.0
I	0	0	1	1	1.0	1.0
Ni	100(2)	1.0×10^{-4}	2000	1000	1.2	1.0
Np	7	7.0×10^{-6}	140	71	1.0	1.0
Pa	64	6.4×10^{-5}	1300	640	1.1	1.0
Pb	5(2)	5.0×10^{-6}	100	51	1.0	1.0
Pu	64	6.4×10^{-5}	1300	640	1.1	1.0
Ra	900(3)	9.0×10^{-4}	18000	9000	2.8	1.2
Sn	170	1.7×10^{-4}	3400	1700	1.3	1.0
Sr	53	5.3×10^{-5}	1100	530	1.1	1.0
Tc	0.3	3.0×10^{-7}	7	4	1.0	1.0
Th	580(2)	5.8×10^{-4}	12000	5300	2.2	1.1
U	1.8	1.8×10^{-6}	37	19	1.0	1.0
Zr	500(2)	5.0×10^{-4}	10000	5000	2.0	1.1

(1) Unless otherwise indicated, distribution coefficients were inferred from soption ratios given by Daniels et al. (1982, 1983).

(2) Inferred from midrange retardation factor for tuffs in compilation by Krauskopf, Table 7-1, National Research Council (1983).

(3) Barium used as chemical analogue for radium (Daniels et al., 1983).

(4) Calculated from Kd using surface area given by Daniels et al. (1982).

(5) Calculated from Eq (7) using $\gamma = 2$, $n = 0.1$.

(6) Calculated from Eq (7) using $\gamma = 2$, $n = 0.2$.

(7) Calculated from Eq (10) using $b = 10\ \mu m$.

(8) Calculated from Eq (10) using $b = 100\ \mu m$.

For a conservative assumption that 2.5% of the total flux would interact with the waste (right-hand axis Figures 22 and Figure 23), total cumulative releases for a flux of 0.5 mm/yr during the next 100,000 yr would constitute only about 10^{-6} (one millionth) of the allowable releases. However, cumulative releases are the basis of compliance with the EPA standards only during the first 10,000 yr following repository closure. We concur with the National Research Council (1983) that the curie release limits based on population dose, as proposed in the current EPA standards, are not ideal surrogates for estimating health effects cause by a repository. However, if the standards must be used, a more reasonable surrogate for assessing the potential hazards after 10,000 yr would be the total curies remaining in the accessible environment, not cumulative curies released to it. This alternative measure of hazards accounts for decay of radioactivity and thus approximates the potential health protection required by the EPA standards for time periods in excess of 10,000 yr.

Figure 24 shows curies remaining in solution in the saturated zone during the first 100,000 yr, assuming a flux of 0.5 mm/yr. The cumulative curies released to the accessible environment from Figure 23 are shown on Figure 24 for comparison. Only two radionuclides, I-129 and C-14, are projected to reach the water table in the first 100,000 yr after repository closure (Figures 23 and 24). The I-129 is the dominant contributor to the minuscule total releases because, by assumption, it is unretarded and its half life, about 17 million years, is much longer than the period for which the releases were calculated. The initial inventory of I-129 in 1000 MTHM of 10-yr old spent fuel is about 33 Ci, whereas 1000 Ci are allowed to be released during the first 10,000 years after closure (Table 1). Thus, the only radionuclide calculated to be released in discernible amounts never exceeds the release standards, even at the time of emplacement in the repository. Carbon-14, the only other nonretarded species, will arrive at the water table simultaneously with iodine, about 30,000 yr after closure for a flux of 0.5 mm/yr. However, because its half life is about 5700 yr, it will decay to insignificant levels soon after it arrives (Figure 24).

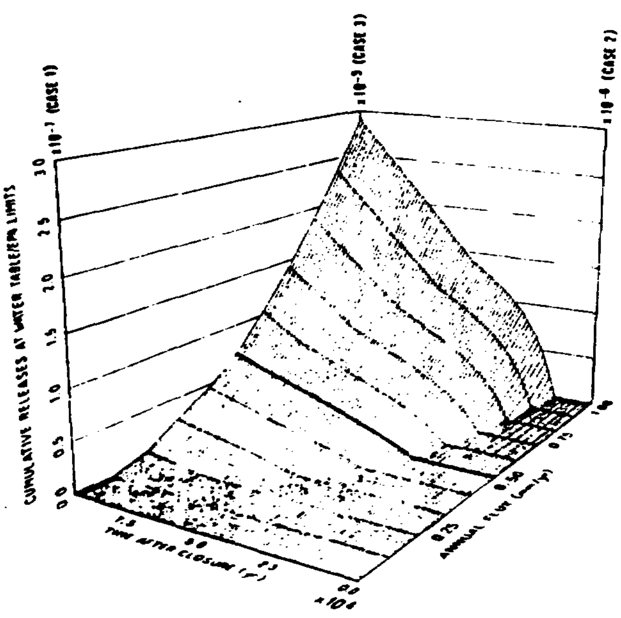


Figure 22. Ratio to the EPA limits of total cumulative curies reaching the water table during the 10,000 yr after repository closure for flux through the unsaturated zone of up to 1 mm/yr; three separate vertical axes show release ratios for three cases of the amount of the total flux contacting the wastes (see text); the three axes also may be interpreted to represent order-of-magnitude variations in uranium solubility for a single amount of interacting water; heavy line accentuates expected upper bound on flux of 0.5 mm/yr; 300-yr waste packages assumed.

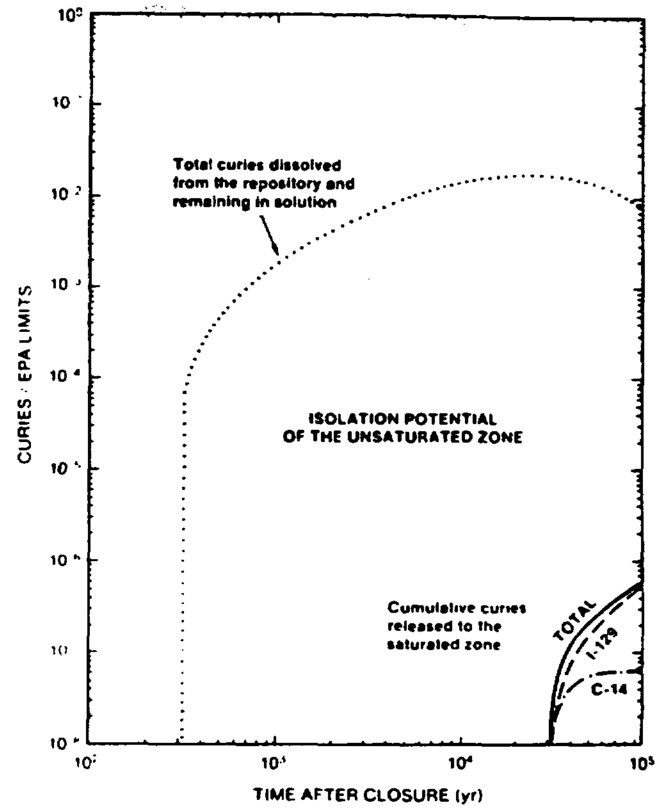


Figure 23. Ratio to the EPA limits of total cumulative curies and curies of individual radionuclides reaching the water table (low curves) and total curies dissolved at the repository and remaining in solution (upper curve) during the 100,000 yr after repository closure for a total flux of 0.5 mm/yr and contact with the waste of 2.5% of this total flux (see right hand axis, Figure 22); the total-curie curve corresponds to the line accentuating 0.5 mm/yr flux on Figure 22; 300-yr waste packages assumed.

Though no sorption was used in our calculations for either iodine or carbon, both elements may be slightly to significantly retarded by other processes. Carbon-14 will probably be retarded to some degree by exchange with existing carbon in carbonate minerals, principally calcite, which occur in slight amounts along the flow paths below the repository level (Spengler et al., 1981). Zeolites, which occur in abundance below the repository level, may effectively sorb iodine as indicated by research to determine how to remove iodine from the effluent streams at reprocessing plants (National Research Council, 1983, pp. 40).

No waste species with matrix retardation values greater than about 3 are projected to reach the water table within the first 100,000 yr after repository closure. Such species include all other radionuclides considered in our calculations (Table 6). Even Tc-99, with an assumed Kd of only 0.3 and a corresponding retardation value for matrix flow of about 7, would not arrive at the water table for about 210,000 yr (30,000-yr flow time multiplied by its retardation factor of 7) for the expected, upper bound on flux of 0.55 mm/yr. It follows that Tc-99 will only move about about 7 m from its emplacement location in the 10,000 yr during which the EPA standards apply. This assumes homogeneous flow in the unsaturated zone and a representative distance of about 300 m from the repository to the water table (Figure 11). Because Tc-99 has a half life of about 200,000 yr, enough of the initial inventory will remain when it arrives at the water table that it will contribute to the small accumulating releases.

Table 7 shows the half lives, arrival times at the water table, and travel distances for 10,000 yr for each radionuclide calculated in the same manner as

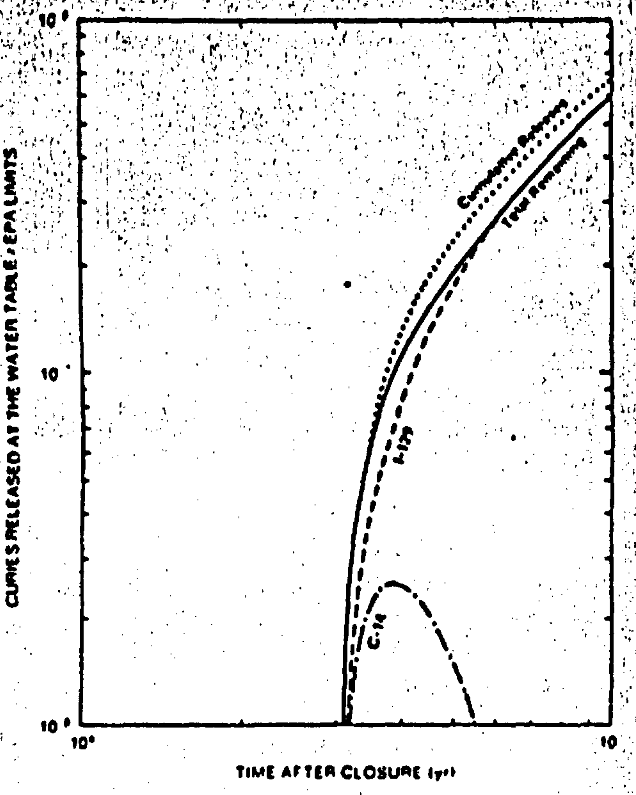


Figure 24. Ratio to the EPA limits of total curies and curies of individual radionuclides remaining below the water table for the same condition as Figure 23; upper curve shows total cumulative curies released to the water table and, for comparison, is the same as the cumulative release curve on Figure 23 (note change in scale of the axes).

for technetium. It is clear from Table 7 that the short-lived fission products responsible for most of the hazards from spent fuel during the first few hundred years after removal from the reactors, predominantly cesium and strontium, will be completely contained within the immediate vicinity of the repository until they have decayed to innocuous levels of radiotoxicity. Long-lived actinides and their short-lived daughter products, primarily radium, will be the main sources of hazards for longer time periods. Most actinides are sufficiently retarded that they will be contained near the repository for millions of years. Neptunium, with an assumed retardation of more than 140 based on a relatively low Kd of 7, will not reach the water table for more than 4 million yr. Other precursors to radium, except uranium, will be so strongly sorbed that they will not reach the water table for tens to hundreds of millions of years. By this time they will have decayed to the extent that little radium will be formed in the saturated zone. Radium is so strongly retarded (Table 6) that whatever is formed along the flow paths will be effectively retained in the unsaturated zone until it essentially

Table 7. First arrival times at the water table and travel distance from the emplacement location during the first 10,000 yr after repository closure for selected radionuclides based on a flux through the unsaturated zone of 0.5 mm/yr, 300-yr waste packages, and contact with the waste of 2.5% of the total flux.

Isotope	Half-life (yr)	Arrival times at the water table (yr)	Travel distances for 10,000 years (m)
^{246}Cm	5.5×10^3		
^{245}Cm	9.3×10^3	1.7×10^8	0.014
^{244}Cm	1.76×10^1		
^{242}Cm	4.5×10^{-1}		
^{243}Am	7.95×10^3	1.2×10^8	0.016
^{242}Am	1.52×10^2		
^{241}Am	4.58×10^2		
^{242}Pu	3.76×10^5		
^{241}Pu	1.32×10^1	3.9×10^7	0.039
^{240}Pu	6.58×10^3		
^{239}Pu	2.44×10^4		
^{238}Pu	8.6×10^1		
^{239}Np	6.6×10^{-3}	4.2×10^6	0.36
^{237}Np	2.14×10^6		
^{238}U	4.51×10^9		
^{236}U	2.39×10^7	1.1×10^5	1.33
^{235}U	7.1×10^8		
^{234}U	2.47×10^5		
^{233}U	1.62×10^5		
^{231}Pa	3.25×10^4	3.9×10^7	0.035
^{232}Th	1.4×10^{10}		
^{230}Th	8.0×10^4	3.6×10^8	0.0043
^{229}Th	7.34×10^3		
^{226}Ra	1.60×10^3	5.4×10^8	0.0028
^{225}Ra	4.05×10^{-2}		
^{210}Pb	2.23×10^1	3.6×10^5	0.1
^{137}Cs	3.0×10^1		
^{135}Cs	3.0×10^6	1.7×10^8	0.006
^{129}I	1.59×10^7	3.8×10^4	50
^{126}Sn	1.0×10^5	1.0×10^9	0.015
^{99}Tc	2.15×10^5	2.1×10^5	1.16
^{93}Zr	9.5×10^5	3.0×10^8	0.003
^{90}Sr	2.8×10^1	3.3×10^7	0.046
^{59}Ni	8.0×10^4	6.0×10^7	0.075
^{14}C	5.73×10^3	3.8×10^4	50

decays away. Uranium, with a Kd of only 1.8, will arrive at the water table in about 1 million yr, at which time U-238 will be the only remaining uranium parent species of significance for radium. The amount of radium in equilibrium with U-238 will remain very low because of the long-lived decay chain.

Considering that we used conservative flux and retardation values of 1 for iodine and carbon and ignored hydrodynamic dispersion and diffusion of radionuclides in the rock matrix, it is likely that even less radioactive waste than shown by Figures 22 through 24 will reach the water table at Yucca Mountain during the first 100,000 yr after repository closure. We assumed that a given percentage of the total, vertically moving flux will intercept and react with the emplaced wastes (see the three separate vertical axes on Figure 22). Additionally, we implicitly assumed that this percentage represents the cross-sectional area of the rock mass transected by vertical contaminant plumes below individual waste canisters. Dispersion and diffusion of radionuclides into the remaining portion of the rock mass would act to reduce concentrations by forming spreading contaminant plumes between the repository and the water table. These phenomena may slow the average velocity of downward radionuclide movement. Diffusion in the immediate vicinity of the waste packages will also tend to reduce solubility-limited dissolution of the waste below the rate that we estimated by assuming full saturation of the entire volume of interacting water with uranium. The amount by which dissolution rates will be slowed will depend on the relative effects of diffusion away from the waste surface and convective water flow to, along, and away from the waste surface (National Research Council, 1983, pp 50; Kerrisk, 1984).

Because groundwater travel time is so long for low flux, the difference cumulative releases to the water table due to 300- or 1000-yr periods of containment in the waste packages would be negligible. Similarly, the additional isolation provided by transport through the saturated zone would significantly affect neither the time of initial releases nor the amount of total releases to the accessible environment. This would be true whether saturated flow were 200 or 2000 yr or whether the accessible environment occurred 2 or 10 km from the repository. Further, the effects of radionuclide retardation will begin to affect releases only tens to hundreds of thousands of years after closure, longer than the period of required compliance with the EPA standards. Geochemical retardation will serve primarily to delay release of the actinides until they have decayed sufficiently to prevent a significant buildup of radium in the accessible environment. Though apparently not necessary for compliance with the EPA regulations, which apply only during the first 10,000 yr, geochemical retardation in the tuffs at Yucca Mountain will provide a significant barrier to longer-term waste movement between the repository level and the human environment.

In summary, it appears, for very conservative assumptions about site conditions, that a repository at Yucca Mountain will isolate nuclear waste from the human environment for tens to hundreds of thousands of years. No radioactivity from the repository will migrate even to the water table immediately beneath the repository for about 30,000 yr, far longer than the period for which compliance with the regulatory release limits must be demonstrated. Then very minor amounts of radioactive carbon and iodine may reach the water table, followed more than 100,000 yr later by small amounts of technetium. Finally, millions of years hence, long-lived actinide may begin to appear at the water table, producing minor amounts of contamination that are caused, in part, by the decay of the actinides to radium. This final source of residual contamination would be essentially negligible, however, because of the slow decay of radium parent species, mostly U-238, that survive the long transit time through the unsaturated environment at Yucca Mountain.

The results shown on Figures 22 through 24 and Table 7 represent conservative judgments about the expected performance of site conditions at Yucca Mountain. These results are used in the following subsections as a baseline for comparing performance under less likely, but possible, site conditions. The next five subsections address, in order,

1. The effects of fracture-flow (Section 4.3.2)
2. The effects of different waste-package containment periods on releases under fracture-flow conditions (Section 4.3.3)
3. The effects of different retardation mechanisms on releases under fracture-flow conditons (Section 4.3.4)
4. The influence of different definitions of the accessible environment on releases under fracture-flow conditions (Section 4.3.5)
5. The effects of a combination of nonconservative site conditions, engineered barriers, and regulatory definitions (Sections 4.3.6).

The variation of different system elements is stressed for fracture flow because for matrix flow their effects are far less significant, given the very long time before any releases could occur, as discussed above.

4.3.2 Unlikely Scenarios Involving Fracture Flow

This section addresses the projected performance of a repository at Yucca Mountain under unlikely flux conditions that could cause water to flow rapidly through fractures in the unsaturated zone. As discussed in Section 3.1.3 and analyzed in Section 4.1, a threshold of flux necessary to sustain fracture flow occurs rather sharply at a value generally corresponding to the saturated hydraulic conductivity of the rock matrix. For both the Topopah Spring and zeolitic Calico Hills units, this threshold value is about 1 mm/yr. Flux greater than this value probably will move through fractures in most portions of these two units. Because the threshold value for the vitric Calico Hills unit is nearly 1000 mm/yr, matrix flow should persist in this unit for any conceivable situations.

As a result, flux greater than 1 mm/yr would cause three types of pathways to the water table, one characterized by fracture flow and the other two by matrix flow. The three pathway types are shown schematically on Figure 25. The fracture-flow pathway (Path A) would transmit the flux in excess of 1 mm/yr through the Topopah Spring and zeolitic Calico Hills units and would occur where the zeolitic Calico Hills unit underlies the repository. For our analyses the zeolitic Calico Hills unit is assumed to underlie 60% of the total repository area, or about $3.6 \times 10^6 m^2$. The first matrix-flow pathway and second overall pathway (Path B) are geometrically coincident with Path A and would transmit the flux of up to the threshold for fracture flow of about 1 mm/yr through the Topopah Spring and zeolitic Calico Hills units. We assumed a representative flow distance to the water table of 150 m for the geometrically coincident fracture and matrix flowpaths through the Topopah Spring (50 m) and zeolitic Calico Hills units (100 m). The second matrix-flow pathway and third overall path (Path C) would transmit all the flux through the portion of the repository underlain by the vitric Calico Hills unit, an area of about $2.4 \times 10^6 m^2$. From the repository to the base of the Topopah Spring unit, this portion of the site would be characterized by fracture flow for flux in excess of 1 mm/yr. From there to the water table, the vitric Calico Hills unit would be able to transmit all flux up to several hundred millimeters per year through the pores in the rock matrix. We conservatively ignored flow through fractures in the Topopah Spring unit for Path C and assumed a representative distance to the water table, entirely within the vitric Calico Hills unit, of 250 m (see Figure 11).

The boundary between the zeolitic (Paths A and B) and vitric (Path C) facies of the Calico Hills unit at Yucca Mountain is poorly defined. The vitric facies occurs at drill holes USW G-3 (Scott and Castellanos, 1984) and USW H-6 (J. H. Robison, USGS, personal communication), whereas the zeolitic facies occurs at the remaining drill holes in the vicinity of the site (Spengler et al., 1979, 1981; Spengler and Muller,

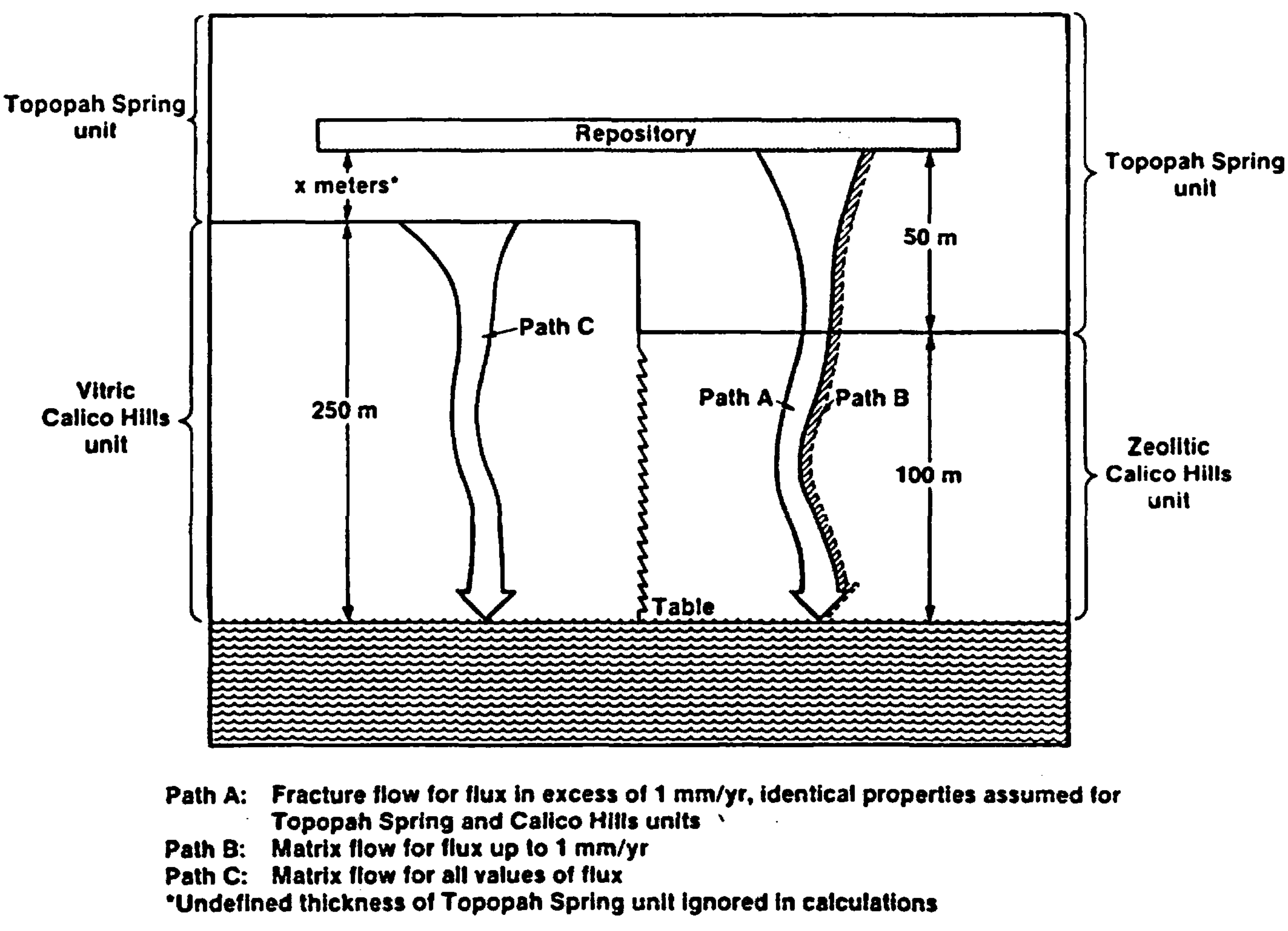


Figure 25. Schematic representation of three types of flow paths used for transport calculations.

1984; Maldonado and Koether, 1983) (see Figure 6 for the location of drill holes relative to the repository area). Using these limited data we assumed that the vitric facies occurs in the southwestern 40% of the repository area.

Projected releases at the water table from each pathway type and for flux of 5 mm/yr are plotted on Figure 26. A flux of 5 mm/yr is used to provide a conservative basis for discussion of fracture-flow scenarios represented by the unlikely occurrence of flux in excess of 1 mm/yr. The 5 mm/yr value corresponds to a highly conservative upper limit on current flux inferred indirectly from climatic evidence as well as to a conservative value for pluvial climates, as discussed in Section 3.1.2. We adopted another conservative assumption for analysis of fracture-flow 'scenarios by allowing the same proportion of water flowing in fractures and in the rock matrix to contact the waste. For Figure 26, we assumed that 2.5% of the flux interacts with the waste. This amount is probably conservative even for matrix flow as discussed in Section 4.2. For fracture flow, an additional level of conservatism is likely, because any water in fractures would tend to rapidly drain past the emplacement holes, even if the fractures were to intercept the holes. Capillary forces would tend to resist the movement of water from the fractures into the larger voids between the waste and the rock wall of the emplacement hole, thus forcing the flow around the holes.

The portion of total releases resulting from transport through fracture pathways in the Topopah Spring and zeolitic Calico Hills unit is indicated by the line labeled Path A on Figure 26. Path B shows releases for the 1 mm/yr flux that continues to flow through the matrix of Topopah Spring and the zeolitic units. Releases from the matrix pathways through the vitric unit are shown by Path C. Combined releases from all three pathways are shown by the same line as Path A, indicating that releases from the fracture-flow pathways would dominate the total releases were fracture flow to occur. The upper, dotted line shows the amount of waste dissolved at the repository normalized to the EPA standards in the same manner as the lower curves. Thus, the regions between the dotted line and the lower curves represent the isolation potential provided by each of the pathways induced by fracture-flow conditions.

Figure 26 indicates that a high flux necessary to sustain fracture flow through the unsaturated zone may cause greater amounts of radioactivity to reach the water table much earlier than would the expected flux of less than 5 mm/yr represented by Figures 22 through 24. Under the reference case for fracture

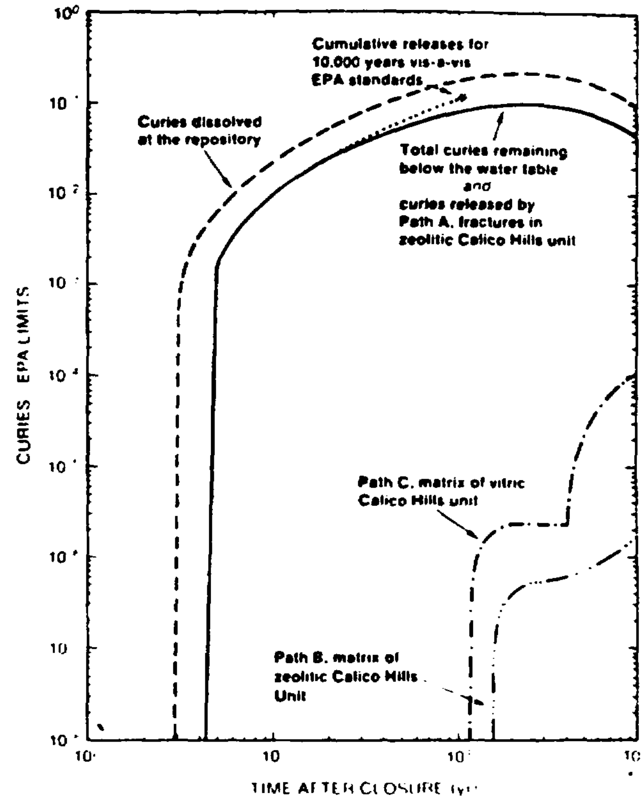
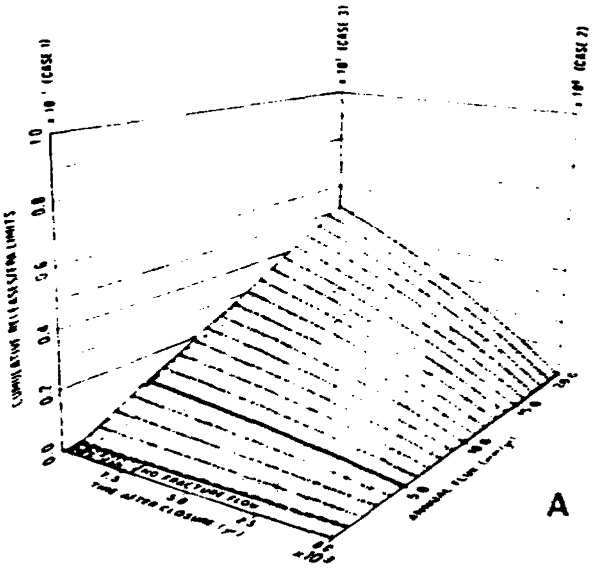


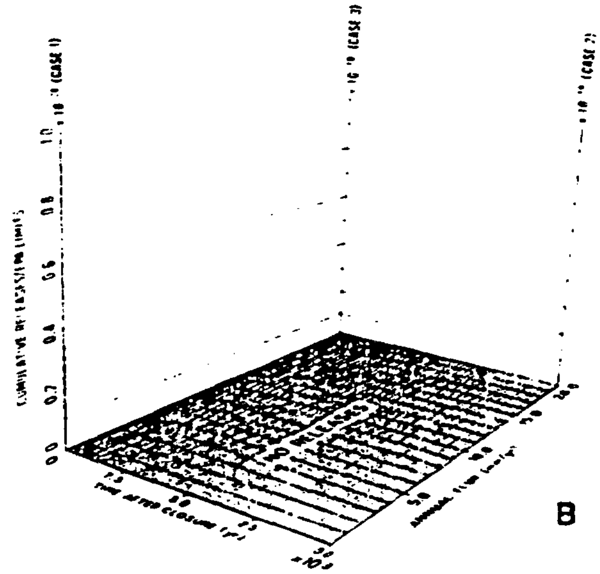
Figure 26. Ratio to the EPA limits of total curies remaining below the water table for 100,000 yr as released by three pathway types caused by a flux of 5 mm/yr (see text) and interaction of 2.5% of this flux with the wastes; 300-yr waste packages assumed; asterisk indicates cumulative releases to the water table at 10,000 yr for comparison with the EPA standard; releases at the repository shown by the upper curve.

flow of 5 mm/yr, flow through the fractures would require only about 30 yr to reach the water table. As a result, several waste species from a repository overlying the zeolitic unit (Figure 26, Path A) would begin arriving at the water table at essentially the same time as they were released from the waste packages, assumed for Figure 26 to be 300 yr after closure. Flow through the matrix of the Topopah Spring and zeolitic Calico Hills units (Figure 26, Path B) would be limited to a flux of 1 mm/yr and would not reach the water table for about 30,000 yr. The matrix of the vitric unit would pass all the flux up to about 1000 mm/yr, and, for a flux of 5 mm/yr, flow through this pathway would not contribute to releases at the water table until about 10,000 yr after closure (Figure 26, Path C).

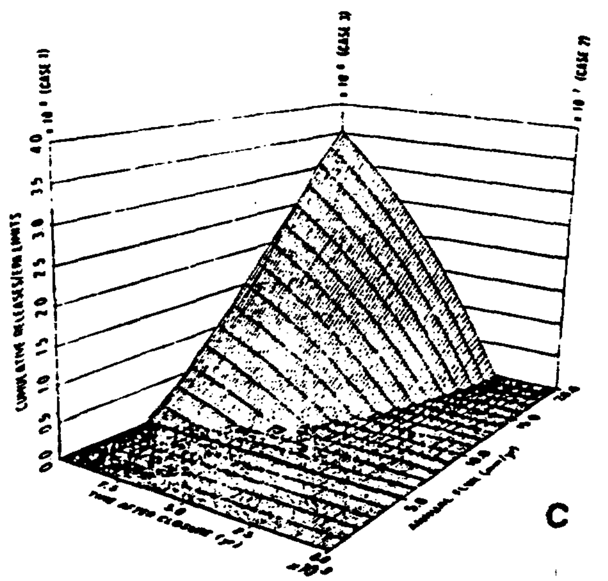
Figure 27 shows the effect of increasing flux up to 20 mm/yr on releases to the water table for 10,000 yr. The reference flux for fracture flow of 5 mm/yr is accentuated on all four parts of Figure 27. An upper limit on flux of 20 mm/yr was selected as a highly



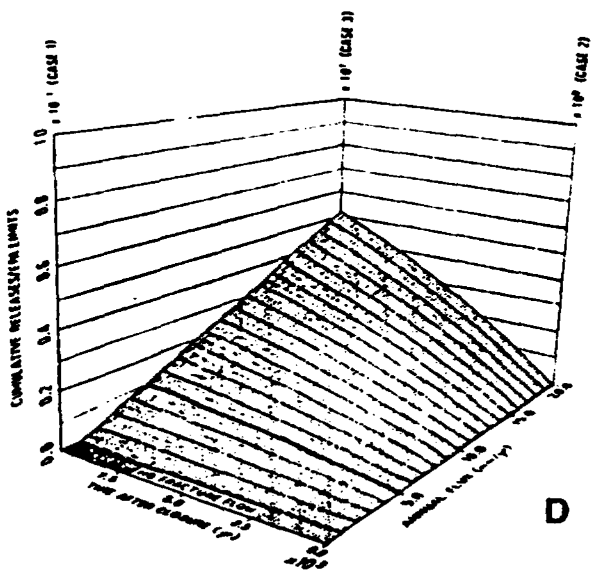
(Path A) **Releases from fracture flow through zeoltic Calico Hills Unit**



(Path B) **Releases from matrix flow of 1 mm/yr through zeolitic Calico Hills Unit**



(Path C) **Releases from matrix flow through vitric Calico Hills Unit**



Total releases to water table (sum of Paths A, B, and C)

Figure 27. Ratio to the EPA limits of total cumulative curies reaching the water table during 10,000 yr for flux up to 20 mm/yr; release ratios shown for three pathways caused by fracture flow conditions (Paths A, B, and C, see text) and for total releases (lower right); 300-yr waste packages assumed; heavy line accentuates reference case for fracture flow of 5 mm/yr; direct sorption was the only retardation mechanism accounted for; the three cases shown by the three vertical axes represent different amounts of the total flux contacting the waste (see text).

conservative upper bound under pluvial conditions. Even under these extreme conditions, cumulative releases would not exceed the EPA limits unless 25% of the total flux were to become saturated with respect to uranium immediately upon contacting the waste (rear axis Figure 27D). This indicates that releases to the water table in violation of the EPA limits would require a combination of several highly unlikely conditions including an almost absurdly high flux, some mechanism for concentrating flow at the waste packages, and complete absence of delaying effects on waste dissolution provided by waste package components after the containment period.

Figure 28 shows the contributions of individual radionuclides to total releases at the water table over 100,000 yr based on a 300-yr waste package, a flux of 5 mm/yr, and an assumption that 2.5% of the flux interacts with the waste. The asterisk on the figure shows the total cumulative releases to the water table for 10,000 yr for direct comparison with the EPA cumulative release limit. The dashed curve leading to the asterisk corresponds to the heavy line on Figure 27D accentuating the reference flux for fracture flow. The cumulative release curve is truncated at 10,000 yr on Figure 28 because this measure, vis-a-vis the EPA standards, applies only during that time period. The uppermost solid curve is noncumulative and represents the total amount of curies remaining in the saturated zone after closure. The remaining curves represent the curies of particular radionuclides remaining below the water table and show the component contributions of individual species to the total curies represented by the upper solid line.

Because the retarding effects of direct sorption along fracture surfaces are small (Table 6), early releases to the water table for fracture-flow pathways, using only sorption as a retarding mechanism, would include both fission products and actinides, total releases for about 30,000 yr would be dominated by Pu-239 and Pu-240 (Figure 28). The slight increases in C-14 and I-129 at about 12,000 yr and Tc-99 at about 40,000 yr are caused by arrival of contaminated water flowing through the matrix of the vitric Calico Hills unit. Tc-99 increase appears later because this element would be slightly retarded in the vitric Calico Hills unit.

Total curies in the saturated zone would continue increasing despite radionuclide decay until about 30,000 yr after repository closure, when radioactive decay, predominatly of Pu-239, would finally overtake new releases (Figure 28). Because cumulative releases to the saturated zone, vis-a-vis the EPA standards, would continue to increase as an essen-

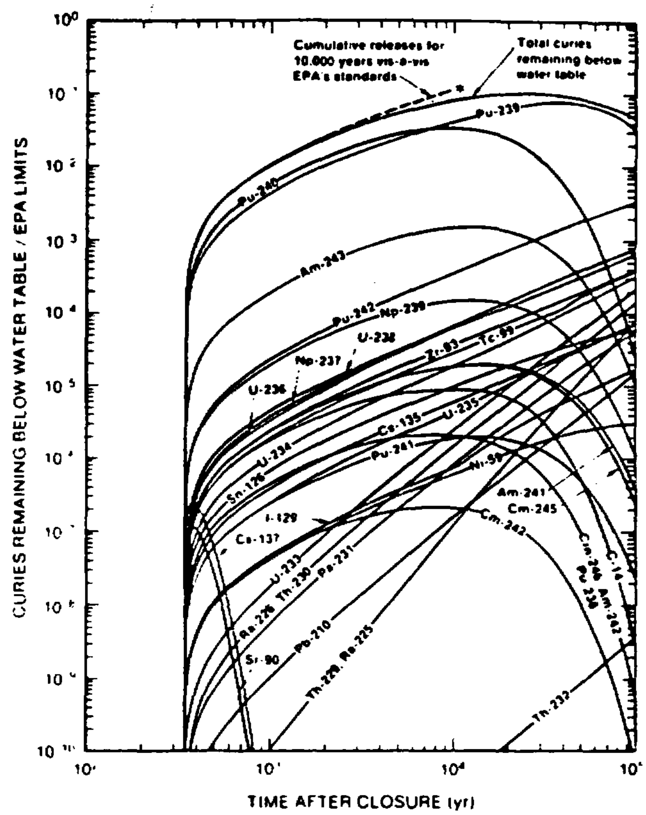


Figure 28. Ratio to the EPA limits of total curies and curies of individual radionuclides remaining below the water table for 100,000 yr for a flux of 5 mm/yr and interaction of the waste with 2.5% of this total flux; releases based on complete and instantaneous failure of all waste packages 300 yr after repository closure; asterisk indicates cumulative releases at the water table for 10,000 yr and is shown for comparison with the EPA standards; the asterisk corresponds to the end point of the line accentuating 5 mm/yr on the lower-right part of Figure 27.

tially straight line after 10,000 yr, Figure 28 indicates that releases calculated by methods required by the EPA for periods longer than 10,000 yr would not account for the decay of radionuclides in the accessible environment. If the short-lived fission products were isolated from the accessible environment for a few hundred years, the distinction between cumulative curies released to and curies remaining in the accessible environment would be relatively insignificant for a time period of 10,000 yr, the period over which the standards apply (Figure 28). However, for periods of tens to hundreds of thousands of years, cumulative releases would tend to increasingly overestimate the hazards to a given population posed by the total curies remaining within the accessible environment.

Because releases by fracture flow appear to occur early and in great amounts (Figures 26 through 28), three items of importance emerge that require careful consideration before concluding that fracture flow would seriously degrade the capabilities of a repository at Yucca Mountain to isolate nuclear wastes. In particular, assumptions about waste-package performance, retardation processes along fractures, and flow and transport through the saturated zone would all become more significant if fracture flow were to occur. To illustrate the effects of each of these items on performance, the fracture-flow baseline case represented by Figures 26 through 28 will be varied independently for each of these items in the following sections.

4.3.3 Effects of Waste-Package Containment on Fracture-Flow Releases

Figure 29 shows total releases at the water table caused by a flux of 5 mm/yr for 300- and 1000-yr containment periods and for a progressively failing containment period. If fracture flow occurs, a 300-yr

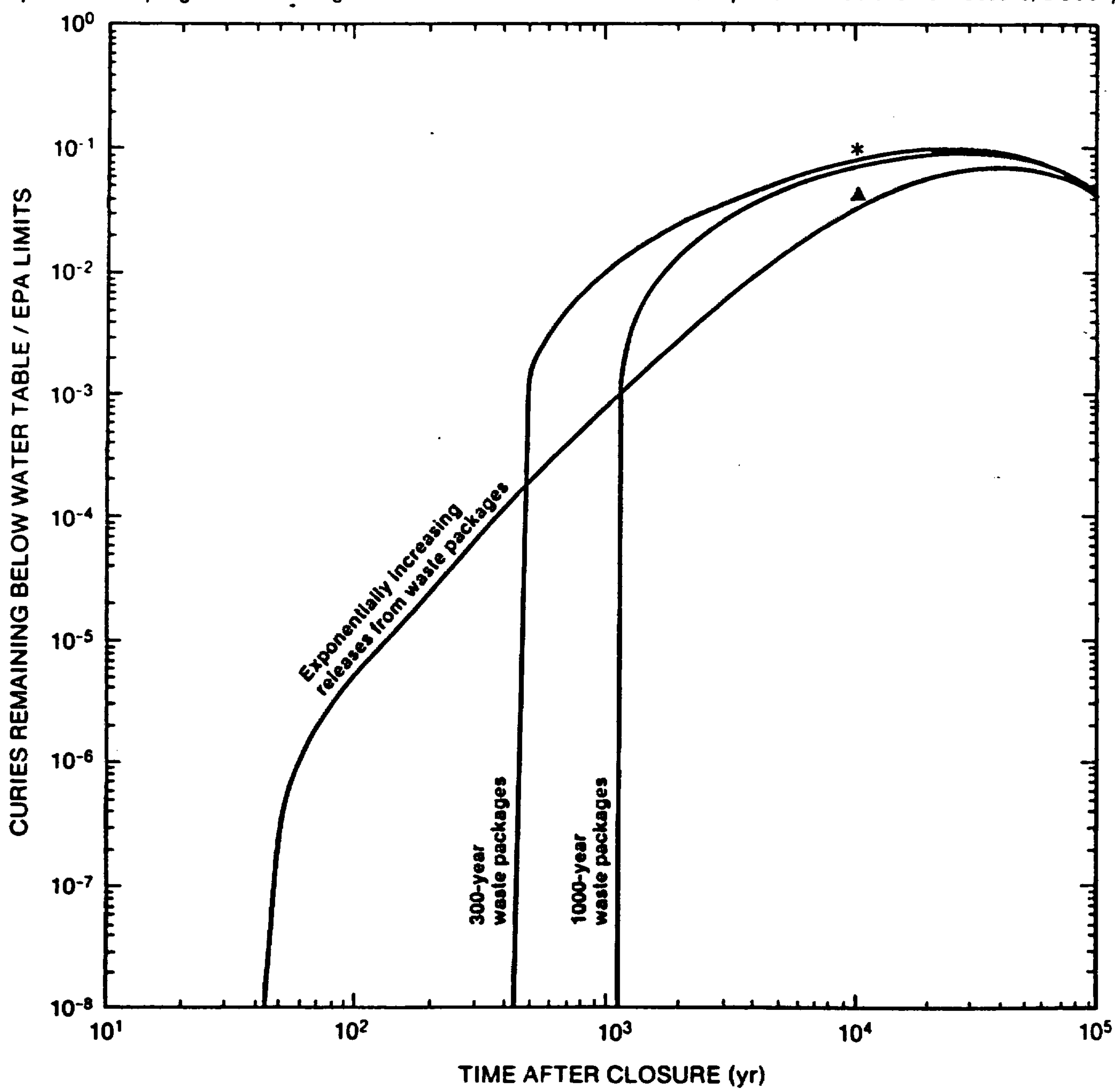


Figure 29. Comparative ratios to the EPA limits of total curies remaining below the water table for 100,000 yr based on 300- and 1000-yr waste packages and waste packages with exponentially increasing loss of containment; total flux assumed to be 5 mm/yr; interacting water assumed to be 2.5% of the total flux; asterisk shows coincident (at the scale of this graph) cumulative releases at 10,000 yr for the 300- and 1000-yr waste packages; solid triangle shows cumulative releases at 10,000 yr for the exponentially decaying waste packages.

waste package may allow curies to accumulate in the saturated zone earlier than for the case where wastes are contained in the repository for 1000 yr. Once they begin, however, the pattern of releases is almost the same for the two containment periods. By about 10,000 yr after closure, the total releases are nearly identical for 300- and 1000-yr waste packages. Thus, the difference in releases resulting from 300- and 1000-yr waste packages is not significant, even if transport times are only tens of years.

More realistic assumptions about waste-package performance, however, do affect projected releases resulting from fracture flow (Figure 29). Releases to the water table for a flux of 5 mm/yr, assuming a mean time-to-failure for waste packages of 10,000 yr (see Section 4.2) clearly demonstrates that more realistic assumptions about waste-package failure significantly lowers releases from fracture flow to the water table for the first 10,000 yr or so. Though all radionuclides will begin to arrive earlier than for waste packages that are 100% effective for a given time, the early releases caused by progressive loss of containment will be small because of the initial limited release rate. In short, progressively decaying waste packages may allow releases to the water table to begin sooner but will limit them to levels well below those produced by waste packages that instantaneously and completely fail either 300 or 1000 yr after repository closure.

Figure 30 shows releases to the water table of individual radionuclides, assuming the progressive increase in release rates from the waste packages. This figure indicates that progressive failure would allow slight amounts of short-lived fission products and actinides, notably Cs-137, Sr-90, and Cm-244, to reach the water table. However, these contaminants would rapidly decay to innocuous levels of radioactivity. At no time would short-lived species jeopardize compliance with the EPA release limits, even if they arrived at the accessible environment 40 yr after closure of the repository (Figure 30). This is because the initial failure rates would be so low as to preclude significant releases of these or any other species.

Figures 29 and 30 are not intended as a projection of actual releases to the water table caused by an actual set of progressively failing waste packages. Their purpose is to indicate that releases to the water table by fracture flow, were it to occur, would probably be less than indicated by adopting an unrealistic assumption that all waste packages will fail completely and simultaneously at either 300 or 1000 yr after repository closure. The likely corrosion rate of canisters in the low flux at Yucca Mountain renders high release rates unrealistic.

4.3.4 Effects of Fracture Retardation on Releases

The conservative nature of Figures 26 through 30, which are based on minimal radionuclide retardation due exclusively to sorption in fractures, is made clear by Figure 31. This figure compares releases to the water table (for unlikely, high flux conditions necessary for fracture flow) under the assumption previously used that only sorption delays radionuclide migration and two different assumptions about the effects of diffusion of radionuclides from fractures into the rock matrix. Diffusion was mentioned in Section 3.2.2 as a potentially significant mechanism for radionuclide movement through fractures. Travis and others (1984) calculated a minimum effective retardation factor of about 400 caused by diffusion from fractures for a nonsorbing species, technetium, and higher values for sorbing species. On the basis of these calculations we chose a highly conservative value of 100 for retardation of all radionuclides in fractures to generate the middle curve (Curve 2) in Figure 31 and more reasonable values of 200 for nonsorbing species (C-14 and I-129), 400 for technetium, and 1000 for all other sorbing species to produce the lower curve (Curve 3). The upper curve (Curve 1) is based on retardation by sorption only and uses the values shown in Table 6 for fracture flow.

It is apparent from the Figure 31 that effective retardation due to diffusion from fractures will significantly delay releases from fracture flow to levels well within the EPA limits. In conjunction with a 300-yr waste package (the basis for all three curves on Figure 31), realistic values for diffusion would delay initial releases to the water table from fracture flow for about 9000 years for the reference flux of 5 mm/yr. The sorbing species would arrive even later; Tc-99 at about 15,000 yr and more highly sorbing species at several decamillenia later. The purpose of Figure 31 is not to project actual releases under fracture-flow conditions, but to indicate the significant effect that radionuclide diffusion from fractures can have, were fracture flow to occur. Even in the unlikely event of significant fracture flow, releases to the water table of nonsorbing species will probably be delayed for thousands of years or longer because of the effective retardation caused by diffusion of radionuclides into and through the slowly moving water in the rock matrix. Sorbing species will probably be delayed for tens of thousands to, perhaps, millions of years, because once the wastes have dif-

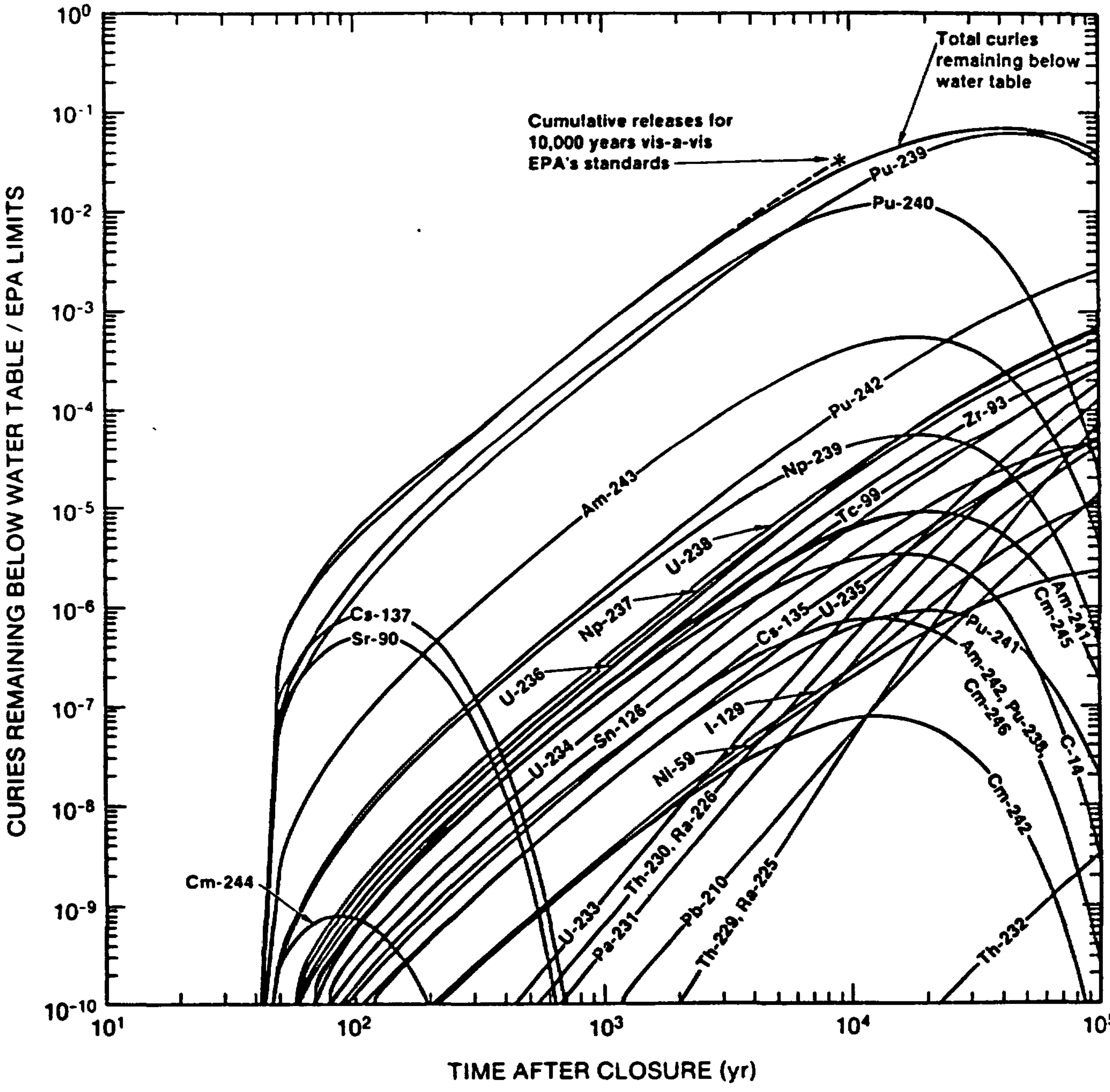


Figure 30. Ratio to the EPA limits of total curies and curies of individual radionuclides remaining below the water table for 100,000 yr based on waste packages with exponentially increasing loss of containment; total flux assumed to be 5 mm/yr; interacting water assumed to be 2.5% of the total flux; cumulative releases at 10,000 yr shown by the asterisk for comparison with the EPA standards.

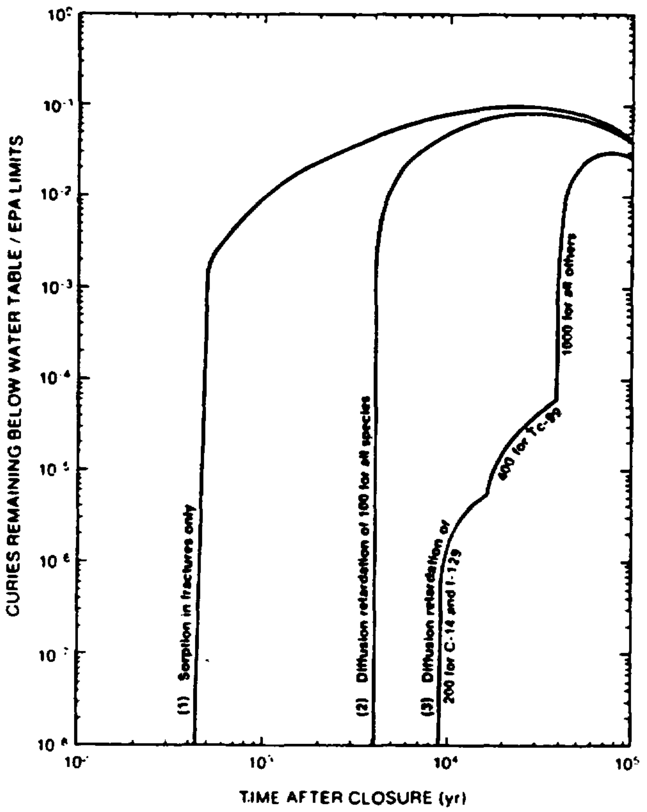


Figure 31. Comparative ratios to the EPA limits of total curies remaining below the water table for 100,000 yr based on three cases of effective retardation of radionuclides relative to fracture water flow: (1) retardation of all waste species by sorption only, (2) effective retardation of 100 by diffusion for all species, and (3) effective retardation by diffusion of 200 for nonsorbing species of C-14 and I-129, 400 for Tc-99, and 1000 for all other species; 300-yr waste packages, 5 mm/yr total flux, and interaction with 2.5% of the total flux assumed.

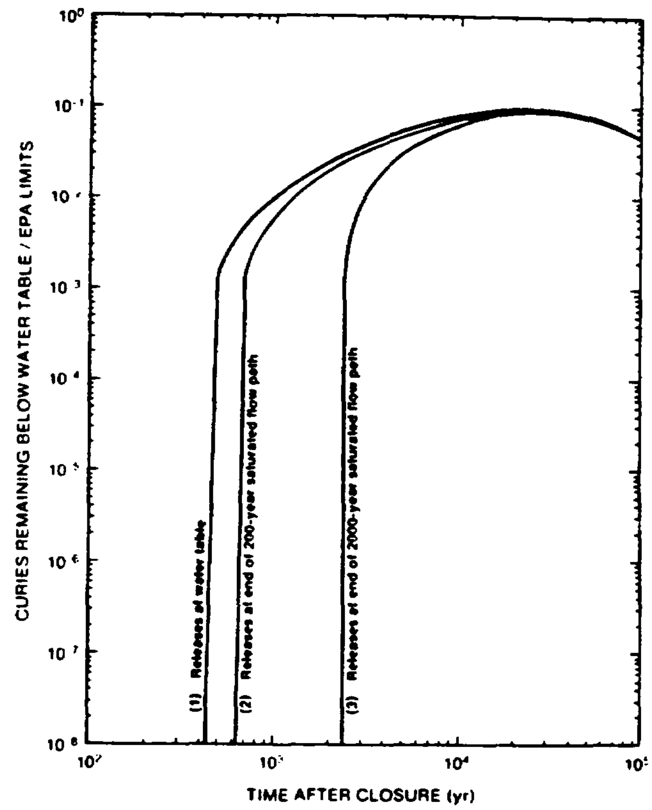


Figure 32. Comparative ratios to the EPA limits of total curies remaining below the water table for three alternative locations of the accessible environment: (1) at the water table, (2) at the end of a 200-yr saturaged flow path, and (3) at the end of a 2000-yr saturated flow path; 300-yr waste packages, 5 mm/yr total flux, interaction with 2.5% of the total flux, and retardation only by sorption assumed.

fused into the matrix, they will be retarded by sorption processes applicable to that flow regime (Travis et al., 1984).

4.3.5 Effects of Saturated Flow Time on Releases to the Accessible Environment

If groundwater flows exclusively through the rock matrix in the unsaturated zone, the contribution of saturated flow time between the repository and the accessible environment would be essentially negligible, as pointed out in Section 4.3.1. However, if flux is sufficient to cause fracture flow through the unsaturated zone, then flow time in the saturated zone would probably be the dominant component of total flow time to the accessible environment, even if it were to occur only 2 km from the repository.

Figure 32 shows releases at the water table and at the end of both 200- and 2000-yr saturated flow paths; assuming 300 yr of complete containment and 5 mm/yr flux. The two assumed flow times in the saturated zone are used to address the uncertainty associated with both the location of the accessible environment and the hydraulic properties along the saturated flow paths. Though the pattern of releases occurring at the water table, shown by the left curve in Figure 32, would not change significantly because of additional flow time through the saturated zone (middle and right curves, Figure 32), initial releases at the end of saturated flow paths would be delayed. Cumulative releases at the end of saturated flow paths would be delayed. Cumulative releases at 10,000 yr would be only slightly less than in the absence of saturated flow.

Only sorption was used as a retarding mechanism for fracture flow in both the unsaturated and the saturated zones. If effective retardation caused by diffusion from fractures were considered, as discussed in Section 4.3.4, actual releases would be much lower than indicated by Figure 32. This is because the diffusion process would be as applicable to fracture flow through the saturated zone as it is to unsaturated flow. For example, if diffusion out of fractures in the saturated zone resulted in an effective retardation of 100, then no radionuclides would arrive at the end of a 200-yr flowpath for 20,000 yr after their arrival at the water table. For these reasons, it appears that the saturated zone provides a significant, though unnecessary, barrier between the proposed repository and the accessible environment, whether that environment were to occur 2 or 10 km from the repository.

4.3.6 Releases under a Combination of More Likely Site Conditions and Engineered Barriers

The previous discussion and figures of releases to the accessible environment have outlined a basis for concluding that a repository at Yucca Mountain would be able to comply with the regulatory requirements presented in Section 1.2. The foregoing results lightly touched upon the myriad possible combinations of site conditions, engineered barriers, and regulatory definitions that affect our ability to predict the performance of a repository. The particular combinations analyzed were selected to focus attention on significant factors affecting overall performance and to establish upper bounds on possible releases under conservative assumptions about individual system components. Hitherto, the advantages of the combined effects of the several multiple barriers have not been considered. Figure 33 does so.

This figure represents a judgment about the potential magnitude and timing of releases from a repository at Yucca Mountain under a combination of nonconservative, but potentially realistic, assumptions for several system components. In this case, expected releases are based on an average flux through the unsaturated zone of 0.1 mm/yr, which is somewhat less than the 0.5 mm/yr used as a conservative reference case in Section 4.3.1. Actual flux may be essentially negligible (see Section 3.1.2), though infrequent recharge pulses probably cause some spatially restricted, short-duration flow through the unsaturated zone at Yucca Mountain. Averaged over time, this flux will not exceed, we assume, 0.1 mm/yr.

Even in the event of episodic fracture flow caused by intense recharge pulses, radionuclide retardation will probably be determined by the sorption values of the rock matrix, because diffusion will tend to drive the waste species into the matrix. Thus, radionuclide transport, if not water flow, will tend to occur within the matrix. This applies to the saturated zone as well as the unsaturated zone. So, contrary to the assumptions for Figure 32, we use retardation values of 100 for all radionuclides in the saturated zone. We assume the accessible environment will occur 2 km from the outer edge of the repository and that flow time along this distance will be 200 yr.

We also assume that the amount of water contacting the emplaced wastes will be much less than the total flux intercepting the area occupied by waste packages. This is because the voids in emplacement holes will most likely act as capillary barriers that effectively prevent movement of water from the rock to the waste canisters (see Section 4.2). For our calculations of releases shown in Figure 33 we used a value of 0.25% of the total flux of 0.1 mm/yr as a basis for dissolving the waste. The failure of waste packages is assumed to follow the exponential form beginning immediately after closure of the repository.

Releases to the accessible environment would be essentially negligible under the assumptions outlined above (Figure 33). Thus, for hundreds of thousands of years, available barriers acting in concert at Yucca Mountain will most likely prevent any contamination of the human environment by radioactive wastes that might be buried there.

If most barriers at Yucca Mountain perform as intended, the most likely case, then the radioactive wastes will be, in essence, permanently and completely separated from the biosphere. The assumptions on which Figure 33 is based must be confirmed by further testing of site conditions and engineering concepts. Therefore, Figure 33 is not a definitive prediction of actual repository performance. It is presented to draw attention away from the more deleterious predictions based on conservative values chosen from the range of known conditions and focus attention on plausible combinations of barriers acting in concert. Because much of this report deals with the effects of unlikely events occurring in unlikely combinations, we present Figure 33 to avoid neglect of the more likely situation represented by consideration of several barriers acting as intended.

4.3.7 Summary of Releases to the Accessible Environment

The preceding sections have presented the results of calculations that show releases of radioactivity to the accessible environment under several scenarios. The individual scenarios represent plausible releases under different combinations of engineered features and site conditions.

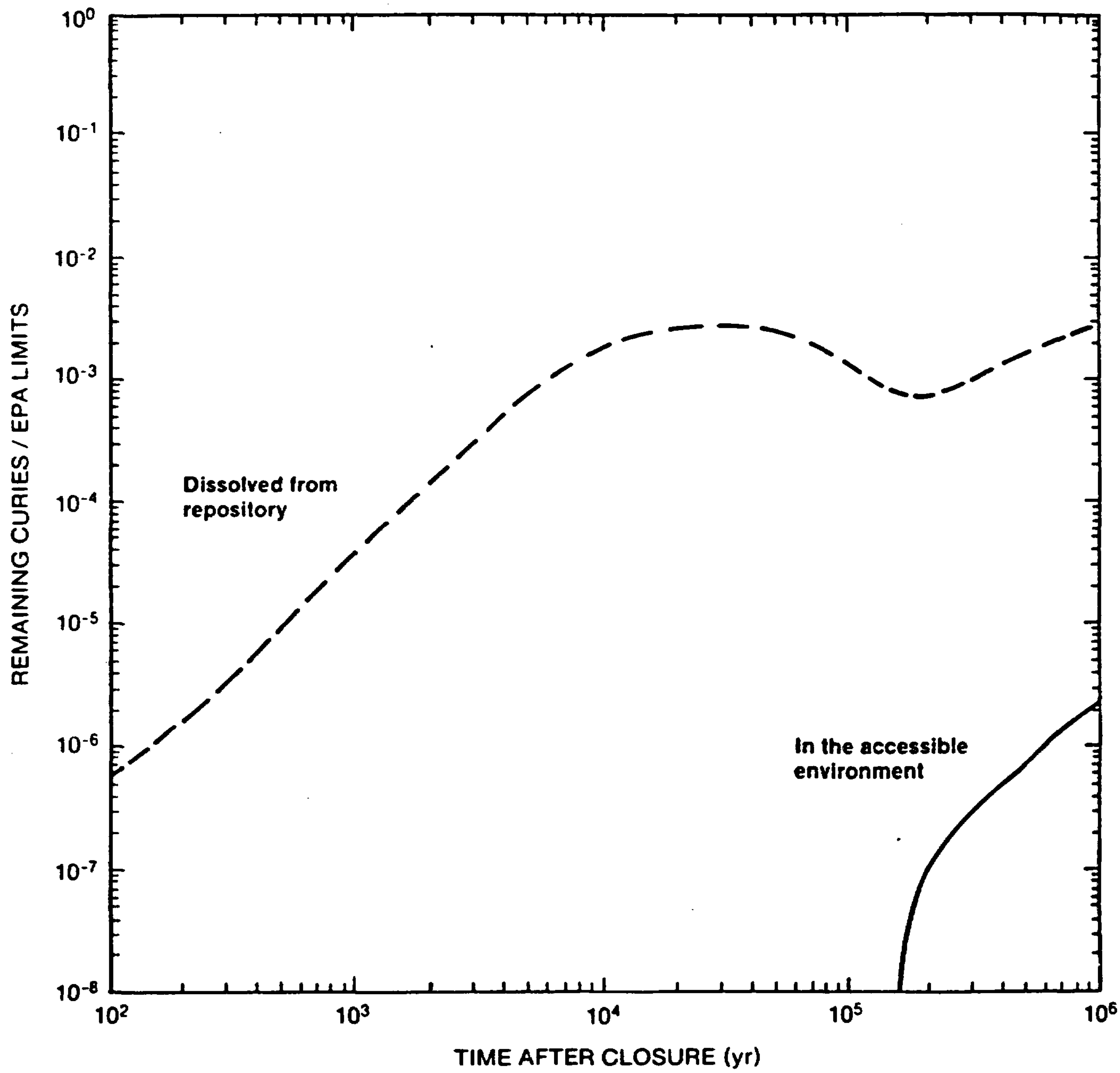


Figure 33. Ratio to the EPA limits of curies remaining in the accessible environment for 1,000,000 yr under a combination of likely barriers acting in concert at Yucca Mountain (see text); all releases shown at the accessible environment (lower curve) are I-129.

The conditions represented by each scenario were chosen from a range of possible values for waste-package lifetimes, total flux through the unsaturated zone, the percentage of the total flux interacting with the emplaced waste (or, alternatively, the solubility of uranium), the length of flow paths to the edge of the accessible environment, and the effectiveness of diffusion in retarding radionuclide migration if fracture flow occurs. In addition, releases to the accessible environment in terms of the EPA standards were expressed in several basic ways: as cumulative releases of all radionuclides in combination, as cumulative releases of individual radionuclides, as total curies remaining in solution that were originally dissolved at the repository, as total curies remaining in solution in the accessible environment, as curies of individual radionuclides remaining in the accessible environment, and as releases to the water table from separate types of flow paths under fracture flow conditions. Releases were projected for time periods of 10,000, 100,000, and 1,000,000 yr. Finally, two other result formats were presented in tabular form, the time of arrival at the water table and the distance traveled in 10,000 yr for individual radionuclides.

Table 8 summarizes the conditions and release formats presented in each of the figures and the tables that show results in Chapter 4. This table indicates the breadth of the parametric variations considered in this study. Because the consideration of alternative parameters was extensive, Table 8 is intended to organize and clarify for the reader our analyses of various combinations of parameters.

Table 8. Summary of conditions considered in calculating potential releases of radionuclides from a repository at Yucca Mountain.

	Figure 21	Figure 22	Figure 23	Figure 24	Figure 26	Figure 27	Figure 28	Figure 29	Figure 30	Figure 31	Figure 32	Figure 33	Table 7
Waste-Package Lifetime													
300 years	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓		✓
1000 years								✓					
exponentially increasing loss of containment								✓	✓			✓	
Total Flux Through the Unsaturated Zone													
0.1 mm/yr (most likely case)												✓	
0.5 mm/yr (reference, upper bound case for current conditions)			✓	✓									✓
5.0 mm/yr (reference case for unlikely fracture flow, likely upper bound for pluvial conditions)					✓		✓	✓	✓	✓	✓		
0 to 1 mm/yr (range for matrix flow)	✓	✓											
0 to 20 mm/yr (range for matrix plus fracture flow)						✓							
Percentage of Flux Interacting With Waste (or) Solubility of U for Case 2													
(Case 1) 0.25% (or) 4×10^{-5} kg/m^3	✓	✓				✓						✓	
(Case 2) 2.5% (or) 4×10^{-4} kg/m^3	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓
(Case 3) 25.0% (or) 4×10^{-3} kg/m^3	✓	✓				✓							
Length of Flow Paths to the Accessible Environment													
150 m (Topopah Spring plus zeolitic Calico Hills)		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
250 m (vitric Calico Hills)		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
150 m and 250 m (see above) plus 200 years of saturated flow											✓	✓	
150 m and 250 m (see above) plus 2000 years of saturated flow											✓		
300 m *(overall representative distance to water table)*													✓
Retardation by Diffusion From Fracture Flow													
0 (flux < 1 mm/yr, no fracture flow)		✓	✓	✓									✓
0 *(sorption only along fracture surfaces)*					✓	✓	✓	✓	✓	✓	✓		
100 (for all species)										✓			
200 (C-14 and I-129), 400 (Tc-99), and 1000 (all other species)										✓		✓	
Types of Releases Normalized to the EPA Standards													
total cumulative releases to the accessible environment		✓	✓	✓	✓	✓	✓	✓	✓				
cumulative releases of individual radionuclides to the accessible environment			✓										
total remaining curies originally dissolved from the repository	✓		✓		✓							✓	
total curies remaining in the accessible environment				✓	✓		✓	✓	✓	✓	✓	✓	
curies of individual radionuclides remaining in the accessible environment				✓			✓		✓			✓	
curies released to the accessible environment by separate flow paths					✓	✓							
Time Period of Plots													
10,000 Years		✓				✓							
100,000 Years	✓		✓	✓	✓		✓	✓	✓	✓	✓		
1,000,000 Years												✓	
Time Required for Individual Radionuclides to Reach the Water Table													✓
Migration Distance of Individual Radionuclides in 10,000 Years													✓

CHAPTER 5. CONCLUSIONS

The unsaturated zone at Yucca Mountain offers several distinct features for isolating nuclear wastes from the human environment. Paramount among these is the small amount of water available to dissolve the waste after it has been emplaced. This water is limited by the arid climate of southern Nevada, which prevents much water from seeping into the earth. The thick unsaturated zone is a result of this limited water flux. The mechanisms of water movement within the unsaturated zone are also uniquely suited to prevent or significantly slow transport of wastes from a repository. Openings in the rock, such as those created by the repository itself, will tend to block the flow of water, quite the opposite of the situation in saturated rocks. This fact lends confidence to a conclusion that little water will be able to reach the waste, and it ameliorates concerns about repository-induced or natural changes that might break, crack, or otherwise fracture the rocks around a repository. Even if the available water is able to contact and dissolve the waste, the low flux in conjunction with the high porosity of the rock matrix will probably limit flow velocities to the extent that no water will reach the water table for tens to hundreds of thousands of years.

Another distinct set of features of the Yucca Mountain site is provided by the volcanic materials from which the rocks are made. The volcanic deposits are highly porous yet, in most cases, highly impermeable. The chemical characteristics of the minerals, particularly zeolites that occur in abundance below the repository level, have strong affinities for ionic waste species, providing a highly sorptive rock mass for delaying waste migration. In combination these properties lend sponge-like properties to the rocks that will tend to draw all or most waste elements into the rock matrix and hold them there for very long times.

By assigning reasonable values to the processes and properties that describe these conditions, the calculations made for this study indicate that no wastes could move the several hundred meters from the repository level to the underlying water table in the 10,000 yr for which performance standards of the EPA will be applied. It is likely that no wastes would arrive at the water table for hundreds of thousands of years, and then only insignificant hazards would be posed by the remaining radioactive material. Under the most likely conditions, the behavior of the waste package will be relatively unimportant in assuring adequate isolation of the waste, because releases from the waste packages can only occur very slowly under the prevailing flux. Similarly, the definition of the accessible environment will have little effect on the overall releases to it, assuming the unsaturated zone is not included within the definition. Water travel time through the unsaturated zone alone is sufficient to provide the necessary isolation. If the assumptions used in this study bound the conditions at Yucca Mountain, it is likely that because of the long water-flow time, geochemical retardation at Yucca Mountain is not essential to ensure compliance with regulatory standards. Geochemical processes will, however, add considerable confidence in the ability of the site to perform satisfactorily.

There are certain unlikely combinations of conditions, each condition in itself unlikely, whereby a repository at Yucca Mountain might release wastes in amounts approaching those permitted by the EPA. High releases might occur primarily because of a peculiar situation that dictates rapid fracture flow through the unsaturated zone if flux exceeds a threshold determined by the carrying capacity of the rock matrix. At this threshold an abrupt transition between matrix and fracture flow occurs, and flow times to the water table discontinuously change from tens of thousands of years for matrix flow to tens of years for fracture flow. However, fracture flow would not be expected to jeopardize complete isolation for 10,000 yr, because it would probably be accompanied by a process whereby wastes would diffuse from fractures into the rock matrix. If fracture flow were to somehow occur in the absence of this diffusion, the performance of waste packages and the buffering isolation provided by the saturated zone might become more significant elements in the overall performance of a repository at Yucca Mountain.

Because data and understanding about water flow and contaminant transport in deep, unsaturated fractured environments are just beginning to emerge, complete dismissal of the rapid-release scenarios is not possible at this time. Therefore, site characterization and theoretical research should focus on establishing the flux through the unsaturated zone at Yucca Mountain, including the manner in which it is temporally and spatially distributed. Such efforts require information about the spatial distribution of hydraulic conductivity as a function of moisture content, development of better understanding of the conditions that dictate the transition between fracture and matrix flow, and empirical and theoretical studies of the magnitude of the diffusion process in unsaturated, fractured media. Until the level of understanding for these items is improved, the pattern of results presented in this report must be considered provisional.

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APPENDIX A
Description of the Theoretical Basis for Transport Calculations

A repository contains M(t) metric tons of heavy metal radioactive waste in a planar horizon distributed over an area expressed in square meters. The repository is assumed to be a height, H, in meters above the water table. The volume of groundwater moving vertically downward through a unit area at the repository horizon per unit time is called the flux and is assumed to be a parameter, F, given in meters per year. Flow in the unsaturated zone is assumed to obey Darcy's law. The boundary of the accessible environment is assumed to occur in the saturated zone a distance 2 to 10 km downgradient from eastern edge of repository. Water flow time through the saturated zone is treated as a constant, T^S.

A.1 Water Flow

Let j, a subscript, identify two components of the medium (porous matrix and fractures) with j=1 denoting the matrix and j=2 denoting the fractures. Darcy's law for flow in both the matrix and fractures is expressed by

$$F_j = -K_j \frac{dh_j}{dl} \quad \text{(m/yr)} \qquad (1)$$

where h_j is hydraulic head, $\frac{dh_j}{dl}$ is the hydraulic gradient, K_j is the hydraulic conductivity, and F_j is called Darcy velocity or Darcy flux. If $\frac{dh_j}{dl}$ is assumed to be -1, the flux through the j^{th} medium cannot exceed the maximum hydraulic conductivity of the j^{th} medium. Thus, if the flux is less than the saturated conductivity of the matrix, $K^s_{j=1}$, the flux is assumed to flow through the porous matrix, and the effective hydraulic conductivity and the gradient will adjust to satisfy equation (1). If the flux is greater than $K^s_{j=1}$, the excess flux, $F_{j=2}$, will flow through fractures of sufficient conductivity to satisfy equation (1).

The average particle velocity of water, V_j, is

$$V_j = \frac{F_j}{n_j} \quad \text{(m/yr)} \tag{2}$$

where n_j is the effective porosity of the j^{th} medium. The water travel time through H_j thickness of unsaturated zone in meters, T^u_j, is

$$T^u_j = \frac{H_j n_j}{F_j} \quad \text{(yr)}. \tag{3}$$

Saturated flow time is treated as a constant, T^s, which was assigned a value of either 0, 200, or 2000 yr (see Section 4.1) for this report. The total water travel time, T_j^w, from repository to accessible environment is the sum of travel time in the saturated zone, T^s, and the travel time in unsaturated zone, and is

$$T_j^w = T_j^u + T^s \quad (yr). \qquad (4)$$

Assigning a value of zero to T^s thus allows a consideration of flow only to the water table.

A.2 Waste Dissolution

The flux that passes through the host rock may intercept the radioactive waste located at the repository. The volume of water that could possibly interact annually with waste, for either matrix or fracture flow, is the total flow through the repository area and is given by

$$Q_j = F_j \cdot A \quad (m^3/yr) \qquad (5)$$

where Q_j is the annual flow rate through j^{th} medium, F_j is the annual flux through j^{th} medium, and A is the area of repository. The annual amount of water in cubic meters actually intercepting the waste emplacement area, q_j, is given by

$$q_j = F_j \cdot A \cdot \alpha_j \quad (m^3/yr) \tag{6}$$

where α_j is the ratio of the area of occupied by the waste (or the effective cross sectional area for water flow associated with the dissolving waste) to the total repository area.

The water intercepting the waste emplacement area may not contact radioactive waste unless the canister fails. We treat canister failure in two ways: (1) a constant lifetime of either 300 or 1000 years represents the time of immediate and simultaneous failure of all canisters, i.e., having a step function at the constant life time, T_f.

$$G(t) = U(t - T_f) \tag{7}$$

where

$$U(t - T_f) = 0 \text{ if } t \leq T_f$$
$$U(t - T_f) = 1 \text{ if } t > T_f$$

(2) canister lifetime is assumed to be a variable in the sense that the lifetime distribution of the canister failure is exponential, i.e., having a probability density function of

$$g(t) = \begin{cases} \frac{1}{\mu} \exp\,(\ t/\mu) & t \geq 0 \\ 0 & t < 0 \end{cases} \tag{8}$$

for which the cumulative distribution is

$$G(t) = \int_{-\infty}^{t} g(y)dy = \begin{cases} 1 - \exp(-t/\mu) & t \geq 0 \\ 0 & t < 0 \end{cases} . \tag{9}$$

The parameter μ is referred to as the mean time to failure of the waste canisters.

Wastes contacted by water are assumed to dissolve congruently with uranium on the mass basis. Thus, given an effective solubility limit of uranium, $S_{i=u}(kg/m^3)$, the expected annual dissolution rate for uranium is given by

$$D_{i=u,j}(t) = q_j \cdot S_{i=u} \cdot G(t) \quad (kg/yr). \tag{10}$$

For the i^{th} radionuclide, the annual dissolution rate is given by

$$D_{i,j}(t) = D_{i=u,j}(t) \cdot \frac{m_i(t)}{m_{i=u}(t)} \quad (kg/yr) \tag{11}$$

where $m_i(t)$ is the inventory of i^{th} radionuclide in kilograms at time, t, and i=u represents uranium. Since radionuclides are assumed to dissolve instantaneously when they are in contact with water, the mass release rate to water is the same as the dissolution rate. The total amount of waste released $\sum_{i=1}^{N} \Delta m_i(t)$, is simply the sum of dissolved amounts for all species.

$$\sum_{i=1}^{N} \Delta m_i(t) = \sum_{i=1}^{N} \sum_{j=1}^{2} D_{i,j}(t) \quad (kg) \tag{12}$$

where N is the number of radionuclide species.

The annual fractional release rate is defined as

$$R = \frac{\sum_{i=1}^{N} \Delta m_i(t)}{\sum_{i=1}^{N} m_i(t)} \quad (yr^{-1}). \tag{13}$$

Substituting equations 11 and 12 for $\sum_{i=1}^{N} \lambda m_i(t)$

$$R = \frac{\sum_{j=1}^{2} D_{i-u,j}(t)}{m_{i-u}(t)} \quad (yr^{-1}) \tag{14}$$

demonstrates that congruent leaching yields an annual fractional release rate for the total waste mass equal to the release rate of uranium. Assuming q_j and S_{i-u} do not change in time and $G(t) = 1$ (in equation 10), $D_{i-u}(t)$ is a constant. If the R is small so that mass removal is negligible over the time period of concern, R is essentially constant because $m_{i-u}(t)$ is dominated by U-238 with a half life of nearly five billion years.

Given the initial inventories of radionuclides, assuming no removal, the amount of mass $m_i(t)$, and $\lambda m_i(t)$ that is present at some time (t) after the initial time (t_o) can be computed analytically by solving a system of ordinary differential equations (Bateman, 1910).

The rate of annual curie releases for the i^{th} species to the water flowing through the j^{th} medium is

$$C_{i,j}(t) = a_i \; D_{i,j}(t) \quad \text{(curies/yr)}. \tag{15}$$

To assess compliance of the annual release rate for each radionuclide with the NRC criterion (10 CFR 60.113), an "NRC Ratio" (NR_i) is calculated as

$$NR_i = \frac{\sum_{j=1} r_{i,j}(t)}{NL_i} \qquad (16)$$

where NL_i is the NRC release limit for i^{th} radionuclide defined in Table 1. Similarly, a total NRC Ratio may be computed with

$$NR = \sum_{i=1}^{N} NR_i \qquad (17)$$

A.3 Radionuclide Transport

The transport time for the i^{th} radionuclide, $T^r_{i,j}$, is related to the water travel time by

$$T^r_{i,j} = Rd_{i,j}\, T^w_j \quad (yr) \qquad (18)$$

where $Rd_{i,j}$ is a dimensionless retardation factor for i^{th} species through j^{th} medium. In porous medium flow, i.e., j=1, the retardation factor is defined as

$$Rd_{i,1} = 1 + \frac{\gamma Kd_i}{n_1} \tag{19}$$

where the γ is the bulk rock density in kg/m^3, Kd_i in m^3/kg is the distribution coefficient or sorption ratio for the i^{th} radionuclide in porous matrix blocks, and n_1 is the effective porosity of the blocks.

In the case of water flow through fractures, i.e. j=2, it is more appropriate, as suggested by Burkholder (1976), to relate the retardation factor to a distribution coefficient Ka_i by the equation

$$Rd_{i,2} = 1 + Rf \cdot Ka_i \tag{20}$$

where Rf is the ratio of surface area to void space (volume) for the fracture opening through which the nuclide is being transported. The Ka_i value is a measure of moles of i^{th} nuclide in the sorbed state per unit surface area divided by the moles of i^{th} nuclide in the dissolved state per unit volume of groundwater when the groundwater and medium are in equilibrium. Since the fracture surface is irregular, the actual surface area with which the nuclide reacts is unknown. A simple practical approach is to express Ka_i relative to the area of an assumed planar fracture surface (Freeze and Cherry, 1979, p. 410). In this case, the retardation factors for fracture flow become

$$Rd_{i,2} = 1 + \frac{2Ka_i}{b} \tag{21}$$

where b is the aperture width of the fracture.

The differential equations describing the transport of radionuclides and their decay products through geologic media with sorption are listed below.

$$Rd_1 \frac{\partial C_1}{\partial t} + v \frac{\partial C_1}{\partial z} = -Rd_1 \lambda_1 C_1$$

$$Rd_2 \frac{\partial C_2}{\partial t} + v \frac{\partial C_2}{\partial z} = -Rd_2 \lambda_2 C_2 + Rd_1 \lambda_1 C_1$$

$$Rd_3 \frac{\partial C_3}{\partial t} + v \frac{\partial C_3}{\partial z} = -Rd_3 \lambda_3 C_3 + Rd_2 \lambda_2 C_2 \tag{22}$$

$$\vdots$$

$$Rd_\ell \frac{\partial C_\ell}{\partial t} + v \frac{\partial C_\ell}{\partial z} = -Rd_\ell \lambda_\ell C_\ell + Rd_{\ell-1} \lambda_{\ell-1} C_{\ell-1}$$

where

C_ℓ = nuclide concentration for the ℓ^{th} member of decay chain, Ci/m^3

Rd_ℓ = retardation factor for the ℓ^{th} member of decay chain

λ_ℓ = decay constant for the ℓ^{th} member of decay chain, 1/yr

v = groundwater velocity, m/yr.

The phenomena of hydrodynamic dispersion and diffusion are not considered in this equation.

A.4 Release to the Accessible Environment

The rate of release of radionuclides from the repository to the accessible environment may be expressed in curies as $C^a_{i,j}$, which is the curie release rate from the repository to the unsaturated zone (Equation 15) delayed by the transport time (Equation 18) and reduced by radioactive decay during the transport time.

The computation of $C^a_{i,j}$ is accomplished by a direct-simulation approach that defines numerical structures that represent the material balances of the ℓ^{th} members of decay chains and all preceding chain members (Equation 22) over a differential length of flow path and a differential time. The annual release rate of curies from the repository, $C_{i,j}(t)$, is represented during transport as a set of discrete lumped slugs. Each slug by definition is of zero size but with spatial coordinates, $(Z_p)_{i,j}$, and a discrete quantity of curies, $(C_p)_{i,j}$, where p is the slug index, $p = 1,2,\ldots N_p$, and N_p is the number of slugs for the i^{th} radionuclide in the j^{th} path.

During a given time step, a new location for each slug is computed from the characteristics of convective mechanisms

$$\frac{d(Z_p)_{i,j}}{dt} = \frac{V}{Rd_{i,j}} \tag{23}$$

where

V = water velocity along the flow path in the z direction.

The new location of the release parcel at k + 1 time step is calculated by

$$(Z_p^{k+1})_{i,j} = (Z_p^k)_{i,j} + \Delta t_k \frac{V}{Rd_{i,j}} \tag{24}$$

where

Δt_k = the time increment for k^{th} time step

$(Z_p^k)_{i,j}$ = the z location of the slug p at the k^{th} time step

$(Z_p^{k+1})_{i,j}$ = the z location of the slug p at the $(k + 1)^{th}$ time step.

The slugs in the flow path and the source term at the repository are adjusted for radioactive decay in each time step by solving the Bateman equations. A five-member chain of equations is used in computation of radionuclide quantities as a function of time. For the decay chains with very rapidly decaying nuclides, each of the short-lived nuclides, i.e., Pu-241, Ra-225, Am-241, Cm-242, Pb-210, and Np-239, is assumed to remain in secular equilibrium with its immediate precursor. No branching ratios are considered in the decay chains.

The rate of release of radionuclides to the accessible environment, C_i^a, is simply the sum of slugs transported across the boundary to the accessible environment per unit time.

Cumulative curies released to the accessible environment for the i^{th} radionuclide, $\bar{C}_i^a$, are numerically approximated by integrating the curie release rates.

$$\bar{C}_i^a(t) = \sum_{j=1}^{2} \sum_{k=1}^{K} C_{i,j}^a(t)\Delta t_k \quad \text{(curies)} \qquad (25)$$

where k is the index for time steps, K is the number of time steps, and Δt_k is the time increment. The performance of the repository is measured by comparing cumulative curies released to accessible environment with the EPA release limits (40 CFR 191). The measure of performance is simply the "EPA release ratio" (ER),

$$ER = \sum_{i=1}^{N} \frac{\bar{C}_i^a(t)}{EL_i} \qquad (26)$$

where EL_i is the EPA limit for i^{th} radionuclide defined in Table 1.

APPENDIX B
Listing of Computer Program Used for Calculations

```
      PROGRAM SAMPLE
      DIMENSION RTCUR(3,100,5,14),RTCUMS(3,100,5,3),RATIO(5,14),
     *DEF(100),SRC(100),DISCI(100),FRN(100)
      DIMENSION PT(11,102),TFAC(100),YR(100),PT1(100),PT2(100),
     *PT3(100),PT4(100),PT5(100),PT6(100),IPAS(70)
      DIMENSION REC(20),TT(3,20),VS(3,20),FL(3,20,3)
     *,DR(3,20,3),TL(3,20,3),FR(3,20,3)
     *,TTC(20),TTB(20),RECM(20),TTM(20)
      DIMENSION AL(5,14),NEC(14),CONI(5,14),CONN(5,14),NLS(5,3),
     *ALS(5,3),SPA(5,14),AM(5,14),RNA(5,3),RCH(8,14),CONIS(5,3),
     *HL(5,14),CUM(5,14),AMS(5,3),RCI(5,14),RCIS(5,3)
      DIMENSION ALP(5,3),CURS(5,3),CUMS(5,3),PAR(5,3),NECS(3),
     *CUR(5,14),SPAS(5,3),PAC(5,3)
      DIMENSION RL(5,14),RLS(5,3),CIR(5,14),CIRS(5,3)
      DIMENSION CITOT(4,20,100),AERAT(4,20,100),AETOT(4,20,100)
      DIMENSION CITOT2(4,20,100),CIRAT(4,20,100),AECID(4,20,100),
     *RC(100,5,14)
      DIMENSION DIS(3,100,5,14),AGIN(100,5,14),RDF(3,5,14),
     *RDFS(3,5,3),AGINS(100,5,3),RCS(100,5,3),
     *SUM(4,100,5,14),SUMS(4,100,5,3),SUC(4,100,5,14),SUCS(4,100,5,3)
      DIMENSION TM21(14),TM31(14),TM41(14),TM51(14),TM32(14),TM42(14),
     *TM52(14),TM53(14),TM54(14),TM43(14),CONIM(5,14),CONNM(5,14),
     *DCON(5,14)
      DIMENSION EP(3),FRA(3),FRF(3),DI(3),FLUX(3,20),MP(20)
      DATA(EP(I),I=1,3)/0.2,0.1,0.08/
      DATA(FRF(I),I=1,3)/0.4,0.6,0.6/
      DATA(FRA(I),I=1,3)/0.25,0.025,0.0025/
      DATA(DI(I),I=1,3)/250.,150.,150./
      DATA(RCH(1,I),I=1,3)/"C-14","TC-99","I-129"/
      DATA(RCH(I,4),I=1,4)/"CM-244","PU-240","U-236","TH-232"/
      DATA(RCH(I,5),I=1,4)/"CM-245","NP-237",
     *"U-233","TH-229"/
      DATA(RCH(I,6),I=1,5)/"CM-246","PU-242",
     *"U-238","U-234","TH-230"/
      DATA(RCH(I,7),I=1,4)/"AM-243","PU-239","U-235","PA-231"/
      DATA(RCH(1,I),I=8,13)/"NI-59","CS-135","SN-126","ZR-93",
     *"SR-90","CS-137"/
      DATA(AM(1,I),I=1,3)/14.,99.,129./
      DATA(AM(I,4),I=1,4)/244.,240.,236.,232./
      DATA(AM(I,5),I=1,4)/245.,             237.,233.,229./
      DATA(AM(I,6),I=1,5)/246.,     242.,      238.,234.,230./
      DATA(AM(I,7),I=1,4)/243.,239.,235.,231./
      DATA(AM(1,I),I=8,13)/59.,135.,126.,93.,90.,137./
      DATA(HL(1,J),J=1,3)/5.73E3,2.15E5,1.59E7/
      DATA(HL(I,4),I=1,4)/17.6,6.58E3,2.39E7,1.4E10/
      DATA(HL(I,5),I=1,4)/9.3E3,             2.44E6,1.62E5,7.34E4/
      DATA(HL(I,6),I=1,5)/5.5E3,      3.79E5,     4.51E9,
     *2.47E5,8.4E4/
      DATA(HL(I,7),I=1,4)/7.95E3,2.44E4,7.1E8,3.25E4/
      DATA(HL(1,I),I=8,13)/8.E4,3.E6,1.E5,9.5E5,29.,30./
      DATA(NEC(I),I=1,14)/1,1,1,4,4,5,4,1,1,1,1,1,1,1/
      DATA(RNA(I,1),I=1,3)/"PU - 241","AM - 241","RA-225"/
      DATA(RNA(I,2),I=1,5)/"AM-242","CM-242","PU-238","RA-226",
     *"PB-210"/
      DATA RNA(1,3)/"NP-239"/
      DATA(ALS(I,1),I=1,3)/5.25E-2,1.51E-3,17.11/
      DATA(ALS(I,2),I=1,5)/4.56E-3,1.54,8.86E-3,4.33E-4,3.11E-2/
      DATA ALS(1,3)/188.28/
      DATA(NECS(I),I=1,3)/3,5,1/
      DATA(SPAS(I,1),I=1,3)/1.12E2,3.24,3.92E4/
      DATA(SPAS(I,2),I=1,5)/9.72,3.32E3,17.5,.908,76.3/
      DATA SPAS(1,3)/2.33E5/
      DATA(RL(1,I),I=1,3)/7.0E3,7.0E5,7.0E4/
      DATA(RL(J,4),J=1,4)/7.E4,7.0E3,7000.,7000./
      DATA(RL(J,5),J=1,4)/7000.,7000.,7000.,7000./
      DATA(RL(J,6),J=1,5)/7000.,7000.,7000.,7000.,7000./
      DATA(RL(J,7),J=1,4)/7000.,7000.,7000.,7000./
      DATA(RL(1,I),I=8,13)/7.E4,7.E4,7.E4,7.E4,7.E4,7.E4/
      DATA(RLS(I,1),I=1,3)/7.E4,7000.,7000./
      DATA(RLS(I,2),I=1,5)/7000.,7.E4,7000.,7000.,7.E4/
      DATA RLS(1,3)/7.E4/
      DATA(RDF(1,1,I),I=1,3)/1.,4.,1./
      DATA(RDF(1,I,4),I=1,4)/1000.,640.,19.,5000./
      DATA(RDF(1,I,5),I=1,4)/1000.,71.,19.,5000./
      DATA(RDF(1,I,6),I=1,5)/1000.,640.,19.,19.,5000./
      DATA(RDF(1,I,7),I=1,4)/1000.,640.,19.,640./
      DATA(RDF(1,1,I),I=8,13)/1000.,2900.,1700.,5000.,530.,2900./
      DATA(RDFS(1,I,1),I=1,3)/640.,1000.,9000./
      DATA(RDFS(1,I,2),I=1,5)/1000.,1000.,640.,9000.,51./
      DATA RDFS(1,1,3)/71./
      DATA(RDF(2,1,I),I=1,3)/1.,7.,1./
      DATA(RDF(2,I,4),I=1,4)/3600.,1300.,37.,12000./
      DATA(RDF(2,I,5),I=1,4)/3600.,140.,37.,12000./
      DATA(RDF(2,I,6),I=1,5)/3600.,1300.,37.,37.,12000./
      DATA(RDF(2,I,7),I=1,4)/3600.,1300.,37.,1300./
      DATA(RDF(2,1,I),I=8,13)/2000.,5000.,3400.,10000.,1100.,5000./
      DATA(RDFS(2,I,1),I=1,3)/1300.,3600.,10000./
      DATA(RDFS(2,I,2),I=1,5)/3600.,3600.,1300.,10000.,100./
      DATA RDFS(2,1,3)/140./
      DATA(RDF(3,1,I),I=1,3)/1.,1.,1./
      DATA(RDF(3,I,4),I=1,4)/1.,1.,1.,1.1/
      DATA(RDF(3,I,5),I=1,4)/1.,1.0,1.0,1.1/
      DATA(RDF(3,I,6),I=1,5)/1.,1.,1.0,1.0,1.1/
      DATA(RDF(3,I,7),I=1,4)/1.,1.,1.0,1./
      DATA(RDF(3,1,I),I=8,13)/1.,1.,1.,1.1,1.,1./
      DATA(RDFS(3,I,1),I=1,3)/1.,1.,1.2/
      DATA(RDFS(3,I,2),I=1,5)/1.,1.,1.,1.2,1.0/
      DATA RDFS(3,1,3)/1.0/
      DATA(TFAC(I),I=1,100)/100*1000./
CCC    DOE-28-10
      DATA(CONI(1,I),I=1,3)/2.2E3,5.35E7,1.33E7/
      DATA(CONI(I,4),I=1,4)/7.57E5,1.39E8,2.43E8,70./
      DATA(CONI(I,5),I=1,4)/0.03E4,3.08E7,2.0E2,9.2E-3/
      DATA(CONI(I,6),I=1,5)/9.20E3,2.07E7,6.73E10,8.38E5,1.48E1/
      DATA(CONI(I,7),I=1,4)/5.38E6,3.31E8,5.23E8,0.23/
      DATA(CONI(1,I),I=8,13)/2.77E4,2.14E7,1.18E6,2.95E7,2.65E7,
     *6.03E7/
      DATA(CONIS(I,1),I=1,3)/4.3E7,3.47E7,1.45E-7/
      DATA(CONIS(I,2),I=1,5)/7.20E4,1.79E2,8.0E6,5.24E-4,6.42E-5/
      DATA CONIS(1,3)/0.23/
CCC    DOE-28-1000
C     DATA(CONI(1,I),I=1,3)/1.09E3,5.35E7,1.33E7/
C     DATA(CONI(I,4),I=1,4)/1.E-99,1.27E8,2.65E8,0.7/
C     DATA(CONI(I,5),I=1,4)/7.58E4,9.43E7,2.22E4,3.94E-1/
C     DATA(CONI(I,6),I=1,5)/7.95E3,2.07E7,6.73E10,9.06E6,2.16E4/
C     DATA(CONI(I,7),I=1,4)/4.9E6,3.20E8,5.56E8,5.43E2/
C     DATA(CONI(1,I),I=8,13)/2.77E4,2.14E7,1.18E6,2.95E7,6.64E-4,
C    *6.7E-3/
C     DATA(CONIS(I,1),I=1,3)/1.06E2,1.79E7,1.89E-3/
C     DATA(CONIS(I,2),I=1,5)/7.92E2,1.96,4.4E3,70.05,0.92/
C     DATA CONIS(1,3)/3.91/
      NCHNS =13
      IPRINT=1
      IRATE=0
      NL=3
C     IV=3
C     IV=1
      IV=2
      C1=1.13E13
      C2=3.1558E7
      C3=.693147
      C5=1.
      SL=4.E-4
      UI=6.7967E7
      AR=6.07E6
      DO 2 I=1,NCHNS
      N=NEC(I)
      DO 2 J=1,N
      AL(J,I)=C3/HL(J,I)
      C4=HL(J,I)*C2
      SPA(J,I)=C1/(C4*AM(J,I))
      CONI(J,I)=CONI(J,I)*C5*.001
    2 CONTINUE
      NP=10
      NT=100
      TOT=0.
      DO 10 I=1,NT
      TOT=TOT+TFAC(I)
   10 YR(I)=TOT
      DO 22 I=1,NP
      REC(I)=I*0.0005
      FLUX(1,I)=REC(I)
      IF(REC(I).LE.1.E-3)GO TO 20
      FLUX(2,I)=0.001
      GO TO 21
   20 FLUX(2,I)=REC(I)
      MP(I)=2
   21 FLUX(3,I)=REC(I)-FLUX(2,I)
      IF (FLUX(3,I).GT.0.) MP(I)=3
   19 NL=MP(I)
      DO 22 L=1,NL
      VS(L,I)=FLUX(L,I)/EP(L)
C      TT(L,I)=DI(L)/VS(L,I)+2000.
      TT(L,I)=DI(L)/VS(L,I)
      DO 22 IC=1,3
      FL(L,I,IC)=AR*FLUX(L,I)*FRA(IC)*FRF(L)
      DR(L,I,IC)=FL(L,I,IC)*SL
      FR(L,I,IC)=DR(L,I,IC)/UI
      TL(L,I,IC)=UI/DR(L,I,IC)
   22 CONTINUE
      DO 24 L=1,3
      PRINT 100
      DO 24 I=1,NP
      PRINT 101,REC(I),FLUX(L,I),VS(L,I),TT(L,I),FL(L,I,1)
     *,FL(L,I,2),FL(L,I,3)
   24 FLUX(L,I)=1000.*FLUX(L,I)
      DO 4 I=1,NCHNS
      N = NEC(I)
      IF(N.EQ.1)GO TO 3
      TM21(I)=1./(AL(2,I)-AL(1,I))
      IF(N.EQ.2)GO TO 3
      TM31(I)=1./(AL(3,I)-AL(1,I))
      TM32(I)=1./(AL(3,I)-AL(2,I))
      IF(N.EQ.3)GO TO 3
      TM41(I)=1./(AL(4,I)-AL(1,I))
      TM42(I)=1./(AL(4,I)-AL(2,I))
      TM43(I)=1./(AL(4,I)-AL(3,I))
      IF(N.EQ.4)GO TO 3
      TM51(I)=1./(AL(5,I)-AL(1,I))
      TM52(I)=1./(AL(5,I)-AL(2,I))
      TM53(I)=1./(AL(5,I)-AL(3,I))
      TM54(I)=1./(AL(5,I)-AL(4,I))
    3 CONTINUE
    4 CONTINUE
      ALP(1,1)=AL(1,5)/ALS(1,1)
      ALP(2,1)=AL(1,5)/ALS(2,1)
      ALP(3,1)=AL(4,5)/ALS(3,1)
      ALP(1,2)=AL(1,6)/ALS(1,2)
      ALP(2,2)=AL(1,6)/ALS(2,2)
      ALP(3,2)=AL(1,6)/ALS(3,2)
      ALP(4,2)=AL(5,6)/ALS(4,2)
      ALP(5,2)=AL(5,6)/ALS(5,2)
```

```
      ALP(1,3)=AL(1,7)/ALS(1,3)
      IF(IV.LE.3)DTT=1050.
      CALL BAT(NCHNS,AL,DTT,NEC,CONI,TM21,TM31,TM41,TM32,TM42,TM43,
     *TM51,TM52,TM53,TM54,DCON)
      DO 197 I=1,NCHNS
      N=NEC(I)
      DO 197 J=1,N
  197 RCI(J,I)=DCON(J,I)
      IF (IV.EQ.1) DTT=50.
      IF (IV.EQ.2) DTT=350.
      IF (IV.EQ.3) DTT=1050.
      CALL BAT(NCHNS,AL,DTT,NEC,CONI,TM21,TM31,TM41,TM32,TM42,TM43,
     *TM51,TM52,TM53,TM54,DCON)
      TOTCI=0.
      DO 167 I=1,NCHNS
      N=NEC(I)
      DO 167 J=1,N
      RCI(J,I)=DCON(J,I)*SPA(J,I)*1000.*1.E-5
C      PRINT 104,I,J,RCI(J,I)
C 104 FORMAT (1X,2I10,1PE10.2)
  167 TOTCI=TOTCI+RCI(J,I)
      PAR(1,1)=DCON(1,5)
      PAR(2,1)=DCON(1,5)
      PAR(3,1)=DCON(4,5)
      PAR(1,2)=DCON(1,6)
      PAR(2,2)=DCON(1,6)
      PAR(3,2)=DCON(1,6)
      PAR(4,2)=DCON(5,6)
      PAR(5,2)=DCON(5,6)
      PAR(1,3)=DCON(1,7)
      DO 168 MI=1,3
      MN=NECS(MI)
      DO 168 MJ=1,MN
      RCIS(MJ,MI)=PAR(MJ,MI)*ALP(MJ,MI)*SPAS(MJ,MI)*1000.*1.E-5
C      PRINT 104,MJ,MI,RCIS(MJ,MI)
  168 TOTCI=TOTCI+RCIS(MJ,MI)
      TOTCI=TOTCI/1000.
C      PRINT 105,TOTCI
C 105 FORMAT (1X,3(1PE10.2,1X))
      IF (IV.EQ.1) DTT=50.
      IF (IV.EQ.2) DTT=350.
      IF (IV.EQ.3) DTT=1050.
      CALL BAT(NCHNS,AL,DTT,NEC,CONI,TM21,TM31,TM41,TM32,TM42,TM43,
     *TM51,TM52,TM53,TM54,DCON)
      DO 198 I=1,NCHNS
      N=NEC(I)
      DO 198 J=1,N
      IF (RCI(J,I).LT.TOTCI) RCI(J,I)=TOTCI
C      RDF(3,J,I)=100.
  198 CONI(J,I)=DCON(J,I)
      PAR(1,1)=DCON(1,5)
      PAR(2,1)=DCON(1,5)
      PAR(3,1)=DCON(4,5)
      PAR(1,2)=DCON(1,6)
      PAR(2,2)=DCON(1,6)
      PAR(3,2)=DCON(1,6)
      PAR(4,2)=DCON(5,6)
      PAR(5,2)=DCON(5,6)
      PAR(1,3)=DCON(1,7)
      DO 196 MI=1,3
      MN=NECS(MI)
      DO 196 MJ=1,MN
      IF (RCIS(MJ,MI).LT.TOTCI) RCIS(MJ,MI)=TOTCI
C      RDFS(3,MJ,MI)=100.
  196 CONIS(MJ,MI)=PAR(MJ,MI)*ALP(MJ,MI)
C      DO 5000 IC=1,3
      IC=2
      T=0.
      DO 283 K=1,NT
      DISCI(K)=0.
  283 SRC(K)=0.
      DO 282 K=1,NT
      T=T+TFAC(K)
      CALL BAT(NCHNS,AL,T,NEC,CONI,TM21,TM31,TM41,TM32,TM42,TM43,
     *TM51,TM52,TM53,TM54,CONN)
C      DEF(K)=1.-EXP(-T/10000.)
      DEF(K)=1.
      FRM(K)=SL*AR*0.0005*0.025*DEF(K)/UI
      DO 200 I=1,NCHNS
      N=NEC(I)
      DO 200 J=1,N
      AGIN(K,J,I)=CONN(J,I)
      RC(K,J,I)=AGIN(K,J,I)*SPA(J,I)*1000.*FRM(K)/RCI(J,I)
      DISCI(K)=DISCI(K)+AGIN(K,J,I)*SPA(J,I)*1000.*FRM(K)
      SRC(K)=SRC(K)+RC(K,J,I)
 200  CONTINUE
      PAC(1,1)=CONN(1,5)
      PAC(2,1)=CONN(1,5)
      PAC(3,1)=CONN(4,5)
      PAC(1,2)=CONN(1,6)
      PAC(2,2)=CONN(1,6)
      PAC(3,2)=CONN(1,6)
      PAC(4,2)=CONN(5,6)
      PAC(5,2)=CONN(5,6)
      PAC(1,3)=CONN(1,7)
      DO 281 MI=1,3
      MN=NECS(MI)
      DO 281 MJ=1,MN
      AGINS(K,MJ,MI)=PAC(MJ,MI)*ALP(MJ,MI)
      RCS(K,MJ,MI)=AGINS(K,MJ,MI)*SPAS(MJ,MI)*1000.*FRM(K)/RCIS(MJ,MI)
      DISCI(K)=DISCI(K)+AGINS(K,MJ,MI)*SPAS(MJ,MI)*1000.*FRM(K)
  281 SRC(K)=SRC(K)+RCS(K,MJ,MI)
  282 CONTINUE
      DO 500 M=1,NF
      PRINT 303,REC(M)
      NL=NP(M)
      DO 211 L=1,NL
      T=0.
      DO 211 KA=1,NT
      CIRAT(L,M,KA)=0.
      CITOT(L,M,KA)=0.
      T=T+TFAC(KA)
      DO 212 IB=1,3
```

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      NA=NECS(IB)
      DO 212 JB=1,NA
      SUCS(L,KA,JB,IB)=0.
  212 SURS(L,KA,JB,IB)=0.
      DO 211 IA=1,NCHNS
      NA=NEC(IA)
      DO 211 JA=1,NA
      DIS(L,KA,JA,IA)=DR(L,M,IC)*AGIN(KA,JA,IA)*DEF(KA)*1000./U1
      RTCUR(L,KA,JA,IA)=0.
      SUC(L,KA,JA,IA)=0.
  211 SUR(L,KA,JA,IA)=0.
      DO 250 L=1,NL
      T=0.
      DO 250 K=1,NT
      T=T+TFAC(K)
      DO 210 IB =1,NCHNS
      NB =NEC(IB)
      DO 210 JB=1,NB
      CONIW(JB,IB)=DIS(L,K,JB,IB)
      IF(K.EQ.1)CONNW(JB,IB)=0.
  210 CONTINUE
      DT=TFAC(K)
      CALL BAT(NCHNS,AL,DT,NEC,CONIW,TM21,TM31,TM41,TM32,TM42,TM43,
     *TM51,TM52,TM53,TM54,DCON)
      DO 216 IB =1,NCHNS
      NB =NEC(IB)
      DO 216 JB=1,NB
      IF (CONIW(JB,IB).LT.1.E-999)GO TO 216
      RATIO(JB,IB)=DCON(JB,IB)/CONIW(JB,IB)
  216 CONTINUE
      IF(M.EQ.1.AND.IC.EQ.2.AND.L.EQ.1)GO TO 218
      GO TO 219
  218 PRINT 302,T
      PRINT 320
      PRINT 309
 219  CONTINUE
      SCIRAT=0.
      SCITOT=0.
      DO 220 IB =1,NCHNS
      NB=NEC(IB)
      DO 220 JB=1,NB
      CONNW(JB,IB)=CONNW(JB,IB)*RATIO(JB,IB)+DCON(JB,IB)*DT
      CUR(JB,IB)=SPA(JB,IB)*CONNW(JB,IB)
      RTCUR(L,K,JB,IB)=DCON(JB,IB)*SPA(JB,IB)
      SCITOT=SCITOT+CUR(JB,IB)
      CIR(JB,IB)=CUR(JB,IB)/RL(JB,IB)
      SCIRAT=SCIRAT+CIR(JB,IB)
      CUM(JB,IB)=CONNW(JB,IB)
  220 CONTINUE
      PAR(1,1)=CONNW(1,5)
      PAR(2,1)=CONNW(1,5)
      PAR(3,1)=CONNW(4,5)
      PAR(1,2)=CONNW(1,6)
      PAR(2,2)=CONNW(1,6)
      PAR(3,2)=CONNW(1,6)
      PAR(4,2)=CONNW(5,6)
      PAR(5,2)=CONNW(5,6)
      PAR(1,3)=CONNW(1,7)
      PAC(1,1)=DCON(1,5)
      PAC(2,1)=DCON(1,5)
      PAC(3,1)=DCON(4,5)
      PAC(1,2)=DCON(1,6)
      PAC(2,2)=DCON(1,6)
      PAC(3,2)=DCON(1,6)
      PAC(4,2)=DCON(5,6)
      PAC(5,2)=DCON(5,6)
      PAC(1,3)=DCON(1,7)
      DO 260 MI=1,3
      MN=NECS(MI)
      DO 266 MJ=1,MN
      CUMS(MJ,MI)=PAR(MJ,MI)*ALP(MJ,MI)
      CURS(MJ,MI)=CUMS(MJ,MI)*SPAS(MJ,MI)
      CIRS(MJ,MI)=CURS(MJ,MI)/RLS(MJ,MI)
  266 RTCURS(L,K,MJ,MI)=PAC(MJ,MI)*ALP(MJ,MI)*SPAS(MJ,MI)
      SCIRAT=SCIRAT+CIRS(MJ,MI)
      SCITOT=SCITOT+CURS(MJ,MI)
  260 CONTINUE
      CIRAT(L,M,K)=SCIRAT
      CITOT(L,M,K)=SCITOT
      CITOT2(L,M,K)=ALOG10(SCITOT)
      NCHNS6=NCHNS-6
      DO 240 IB =1,NCHNS6
      NB =NEC(IB)
      DO 240 JB=1,NB
      IF(M.EQ.1.AND.IC.EQ.2.AND.L.EQ.1)GO TO 223
      GO TO 224
  223 CONTINUE
      IF(IB.EQ.2.OR.IB.EQ.3)GO TO 221
      IF(JB.NE.1)GO TO 221
      IF(IB.EQ.1.OR.IB.EQ.8)GO TO 340
      IF(IB.EQ.4)GO TO 341
      IF(IB.EQ.5)GO TO 342
      IF(IB.EQ.6)GO TO 343
      IF(IB.EQ.7)GO TO 344
 340  PRINT 321
      PRINT 315
      GO TO 221
 341  PRINT 321
      PRINT 311
      GO TO 221
 342  PRINT 321
      PRINT 312
      GO TO 221
 343  PRINT 321
      PRINT 313
      GO TO 221
 344  PRINT 321
      PRINT 314
  221 CONTINUE
      PRINT 310,NCH(JB,IB),DIS(L,K,JB,IB),CUR(JB,IB),CUM(JB,IB),
     *AGIN(K,JB,IB),CIR(JB,IB),RC(K,JB,IB),RTCUR(L,K,JB,IB)
      IF(IB.NE.3)GO TO 230
      DO 231 I7=8,13
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231 PRINT 310,RCH(JB,I7),DIS(L,K,JB,I7),CUR(JB,I7),CUM(JB,I7),
   *AGIN(K,JB,I7),CIR(JB,I7),RC(K,JB,I7),RTCUR(L,K,JB,I7)
230 CONTINUE
    IF(IB.EQ.5) GO TO 5
    IF(IB.EQ.6)GO TO 6
    IF(IB.EQ.7) GO TO 7
    GO TO 224
5   GO TO (8,224,224,9)JB
8   PRINT 317,RNA(1,1),CURS(1,1),CUMS(1,1),AGINS(K,1,1),CIRS(1,1),
   *RCS(K,1,1),RTCURS(L,K,1,1)
    PRINT 317,RNA(2,1),CURS(2,1),CUMS(2,1),AGINS(K,2,1),CIRS(2,1),
   *RCS(K,2,1),RTCURS(L,K,2,1)
    GO TO 224
9   PRINT 317,RNA(3,1),CURS(3,1),CUMS(3,1),AGINS(K,3,1),CIRS(3,1),
   *RCS(K,3,1),RTCURS(L,K,3,1)
    GO TO 224
6   GO TO (11,12,224,224,13)JB
11  PRINT 317,RNA(1,2),CURS(1,2),CUMS(1,2),AGINS(K,1,2),CIRS(1,2),
   *RCS(K,1,2),RTCURS(L,K,1,2)
    PRINT 317,RNA(2,2),CURS(2,2),CUMS(2,2),AGINS(K,2,2),CIRS(2,2),
   *RCS(K,2,2),RTCURS(L,K,2,2)
    GO TO 224
12  PRINT 317,RNA(3,2),CURS(3,2),CUMS(3,2),AGINS(K,3,2),CIRS(3,2),
   *RCS(K,3,2),RTCURS(L,K,3,2)
    GO TO 224
13  PRINT 317,RNA(4,2),CURS(4,2),CUMS(4,2),AGINS(K,4,2),CIRS(4,2),
   *RCS(K,4,2),RTCURS(L,K,4,2)
    PRINT 317,RNA(5,2),CURS(5,2),CUMS(5,2),AGINS(K,5,2),CIRS(5,2),
   *RCS(K,5,2),RTCURS(L,K,5,2)
    GO TO 224
7   GO TO (14,224,224,224)JB
14  PRINT 317,RNA(1,3),CURS(1,3),CUMS(1,3),AGINS(K,1,3),CIRS(1,3),
   *RCS(K,1,3),RTCURS(L,K,1,3)
224 CONTINUE
240 CONTINUE
250 CONTINUE
    DO 290 L=1,NL
    T=0.
    DO 280 K=1,NT
    T=T+TFAC(K)
    DO 270 IB =1,NCHNS
    NB=NEC(IB)
    DO 270 JB=1,NB
    RT=TT(L,M)*RDF(L,JB,IB)
    RTT=TOT-RT
    IF (RTT.LT.0..OR.T.GT.RTT)GO TO 270
    KRT=0
    TRT=T+RT
    DO 278 KT=1,NT
    IF (TRT.LT.0.)GO TO 279
    TRT=TRT-TFAC(KT)
278 KRT=KRT+1
279 CONTINUE
    SUR(L,KRT,JB,IB)=SUR(L,KRT,JB,IB)
   *+RTCUR(L,KRT,JB,IB)*DEP(K)/DEP(KRT)*TFAC(K)
270 CONTINUE
    DO 280 MI=1,3
    MN=NECS(MI)
    DO 280 MJ=1,MN
    RTS=TT(L,M)*RDFS(L,MJ,MI)
    RTTS=TOT-RTS
    IF(RTTS.LT.0..OR.T.GT.RTTS)GO TO 280
    KRTS=0
    TRTS=T+RTS
    DO 288 KT=1,NT
    IF (TRTS.LT.0.) GO TO 289
    TRTS=TRTS-TFAC(KT)
288 KRTS=KRTS+1
289 CONTINUE
    SURS(L,KRTS,MJ,MI)=SURS(L,KRTS,MJ,MI)
   *+RTCURS(L,KRTS,MJ,MI)*DEP(K)/DEP(KRTS)*TFAC(K)
280 CONTINUE
290 CONTINUE
    DO 460 K=1,NT
    DO 493 IA=1,NCHNS
    NA=NEC(IA)
    DO 493 JA=1,NA
493 SUR(4,K,JA,IA)=SUR(1,K,JA,IA)+SUR(2,K,JA,IA)+SUR(3,K,JA,IA)
    DO 494 IB=1,3
    NB=NECS(IB)
    DO 494 JB=1,NB
494 SURS(4,K,JB,IB)=SURS(1,K,JB,IB)+SURS(2,K,JB,IB)+SURS(3,K,JB,IB)
460 CONTINUE
    DO 296 L=1,NL
    DO 291 IA=1,NCHNS
    NA=NEC(IA)
    DO 291 JA=1,NA
    STOT=0.
    STOTC=0.
    DO 291 K=1,NT
    STOT=STOT+SUR(L,K,JA,IA)/RL(JA,IA)
    IF (K.EQ.1.OR.STOT.EQ.0.)GO TO 297
    STOTC=STOTC*RTCUR(L,K,JA,IA)/RTCUR(L,K-1,JA,IA)
   **DEP(K-1)/DEP(K)+SUR(L,K,JA,IA)
   */RL(JA,IA)
297 CONTINUE
    SUR(L,K,JA,IA)=STOT
    SUC(L,K,JA,IA)=STOTC
291 CONTINUE
    DO 292 IB=1,3
    NB=NECS(IB)
    DO 292 JB=1,NB
    IF (IB.NE.1) GO TO 281
    MB=5
    IF (JB.EQ.1.OR.JB.EQ.2) MA=1
    IF(JB.EQ.3) MA=4
    GO TO 283
281 IF (IB.NE.2) GO TO 282
    MB=6
    IF(JB.EQ.1.OR.JB.EQ.2.OR.JB.EQ.3) MA=1
    IF(JB.EQ.4.OR.JB.EQ.5) MA=5
    GO TO 283
282 IF(IB.EQ.3) MB=7
    IF(JB.EQ.1) MA=1
283 CONTINUE
    STOTS=0.
    STOTCS=0.
    DO 292 K=1,NT
    STOTS=STOTS+SURS(L,K,JB,IB)/RLS(JB,IB)
    IF (K.EQ.1.OR.STOTS.EQ.0.) GO TO 298
    STOTCS=STOTCS*RTCURS(L,K,JB,IB)/RTCURS(L,K-1,JB,IB)
   **DEP(K-1)/DEP(K)
   *+SURS(L,K,JB,IB)/RLS(JB,IB)
298 CONTINUE
    SURS(L,K,JB,IB)=STOTS
    SUCS(L,K,JB,IB)=STOTCS
292 CONTINUE
    DO 295 K=1,NT
    SAECID=0.
    SAETOT=0.
    SAERAT=0.
    DO 293 IA=1,NCHNS
    NA=NEC(IA)
    DO 293 JA=1,NA
    SAECID=SAECID+SUC(L,K,JA,IA)
    SAETOT=SAETOT+SUR(L,K,JA,IA)*RL(JA,IA)
293 SAERAT=SAERAT+SUR(L,K,JA,IA)
    DO 294 IB=1,3
    NB=NECS(IB)
    DO 294 JB=1,NB
    SAECID=SAECID+SUCS(L,K,JB,IB)
    SAETOT=SAETOT+SURS(L,K,JB,IB)*RLS(JB,IB)
294 SAERAT=SAERAT+SURS(L,K,JB,IB)
    AECID(L,M,K)=SAECID
    AETOT(L,M,K)=SAETOT
    AERAT(L,M,K)=SAERAT
295 CONTINUE
296 CONTINUE
    DO 360 K=1,NT
    DO 393 IA=1,NCHNS
    NA=NEC(IA)
    DO 393 JA=1,NA
    SUR(4,K,JA,IA)=SUR(1,K,JA,IA)+SUR(2,K,JA,IA)+SUR(3,K,JA,IA)
393 SUC(4,K,JA,IA)=SUC(1,K,JA,IA)+SUC(2,K,JA,IA)+SUC(3,K,JA,IA)
    DO 394 IB=1,3
    NB=NECS(IB)
    DO 394 JB=1,NB
    SURS(4,K,JB,IB)=SURS(1,K,JB,IB)+SURS(2,K,JB,IB)+SURS(3,K,JB,IB)
394 SUCS(4,K,JB,IB)=SUCS(1,K,JB,IB)+SUCS(2,K,JB,IB)+SUCS(3,K,JB,IB)
    CIRAT(4,M,K)=CIRAT(1,M,K)+CIRAT(2,M,K)+CIRAT(3,M,K)
    CITOT(4,M,K)=CITOT(1,M,K)+CITOT(2,M,K)+CITOT(3,M,K)
    AETOT(4,M,K)=AETOT(1,M,K)+AETOT(2,M,K)+AETOT(3,M,K)
    AERAT(4,M,K)=AERAT(1,M,K)+AERAT(2,M,K)+AERAT(3,M,K)
    AECID(4,M,K)=AECID(1,M,K)+AECID(2,M,K)+AECID(3,M,K)
360 CONTINUE
    DO 366 L=1,NL
    IF (IC.NE.2) GO TO 351
    IF (IPRINT.NE.1) GO TO 350
    PRINT 103,L
    PRINT 322
    DO 330 K=1,NT
    PRINT 323,TR(K),CITOT(L,M,K),CIRAT(L,M,K),AETOT(L,M,K),
   *AERAT(L,M,K),SUR(L,K,1,1),SUR(L,K,1,2),
   *SUR(L,K,1,3),SUR(L,K,1,8),SUR(L,K,1,9),SUR(L,K,1,10)
330 CONTINUE
    PRINT 326
    DO 331 K=1,NT
    PRINT 323,TR(K),SUR(L,K,1,11),SUR(L,K,1,12),SUR(L,K,1,13),
   *SUR(L,K,1,4),SUR(L,K,2,4),SUR(L,K,3,4),SUR(L,K,4,4),
   *SUR(L,K,1,5),SURS(L,K,1,1),SURS(L,K,2,1)
331 CONTINUE
    PRINT 327
    DO 332 K=1,NT
    PRINT 323,TR(K),SUR(L,K,2,5),SUR(L,K,3,5),SUR(L,K,4,5),
   *SURS(L,K,3,1),SUR(L,K,1,6),SURS(L,K,1,2),SUR(L,K,2,2),
   *SUR(L,K,2,6),SURS(L,K,3,2),SUR(L,K,3,6)
332 CONTINUE
    PRINT 328
    DO 333 K=1,NT
    PRINT 323,TR(K),SUR(L,K,4,6),SUR(L,K,5,6),SURS(L,K,4,2),
   *SURS(L,K,5,2),SUR(L,K,1,7),SURS(L,K,1,3),SUR(L,K,2,7),
   *SUR(L,K,3,7),SUR(L,K,4,7),AECID(L,M,K)
333 CONTINUE
350 CONTINUE
    IF (IPRINT.NE.2) GO TO 351
    PRINT 322
    DO 430 K=1,NT
    PRINT 323,TR(K),CITOT(L,M,K),CIRAT(L,M,K),AETOT(L,M,K),
   *AERAT(L,M,K),SUC(L,K,1,1),SUC(L,K,1,2),
   *SUC(L,K,1,3),SUC(L,K,1,8),SUC(L,K,1,9),SUC(L,K,1,10)
430 CONTINUE
    PRINT 326
    DO 431 K=1,NT
    PRINT 323,TR(K),SUC(L,K,1,11),SUC(L,K,1,12),SUC(L,K,1,13),
   *SUC(L,K,1,4),SUC(L,K,2,4),SUC(L,K,3,4),SUC(L,K,4,4),
   *SUC(L,K,1,5),SUCS(L,K,1,1),SUCS(L,K,2,1)
431 CONTINUE
    PRINT 327
    DO 432 K=1,NT
    PRINT 323,TR(K),SUC(L,K,2,5),SUC(L,K,3,5),SUC(L,K,4,5),
   *SUCS(L,K,3,1),SUC(L,K,1,6),SUCS(L,K,1,2),SUCS(L,K,2,2),
   *SUC(L,K,2,6),SUCS(L,K,3,2),SUC(L,K,3,6)
432 CONTINUE
    PRINT 328
    DO 433 K=1,NT
    PRINT 323,TR(K),SUC(L,K,4,6),SUC(L,K,5,6),SUCS(L,K,4,2),
   *SUCS(L,K,5,2),SUC(L,K,1,7),SUCS(L,K,1,3),SUC(L,K,2,7),
   *SUC(L,K,3,7),SUC(L,K,4,7),AECID(L,M,K)
433 CONTINUE
351 CONTINUE
366 CONTINUE
    PRINT 102
    DO 361 K=1,NT
    PRINT 101,TR(K),CIRAT(4,M,K),CITOT(4,M,K),AETOT(4,M,K),
   *AERAT(4,M,K),AECID(4,M,K)
361 CONTINUE
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500 CONTINUE
100 FORMAT(1H1,3X,"RECHARGE M/YR",3X," FLUX M/YR   ",
   *3X,"VELOCITY M/YR",2X,
   *"TRAVEL TIME YR",2X,"25% FLUX CUM/YR",2X,"2.5% FLUX",5X,
   *".25% FLUX")
101 FORMAT(5X,7(1PE10.2,5X))
102 FORMAT(//8X,"TIME",10X,"CIRAT",10X,"CITOT",10X,"AETOT",
   *10X,"AERAT",10X,"AECID")
103 FORMAT(//,"*******",I2,"TH MEDIUM *******")
300 FORMAT(10X,"UNDECAYED")
301 FORMAT(5X,A8,"GM=",1PE10.2,10X,"CI=",1PE10.2)
302 FORMAT(80X,"TIME =",1PE10.2)
307 FORMAT(15X,A8)
308 FORMAT(/49X,"RECHARGE RATE =",1PE10.2,"(MM/YR)")
309 FORMAT(26X,"DISS RATE GM/YR",4X,"CUM CI",9X,"CUM GMS",9X,
   *"KGMS LEFT",6X,"CUM CI/RL",4X,"NRC-RATIO",4X,"RTCUR")
310 FORMAT(17X,A8,5(1PE10.2,6X),1PE10.2,4X,1PE10.2)
311 FORMAT(3X,"CHAIN 1 - THORIUM SERIES")
312 FORMAT(3X,"CHAIN 2 - NEPTUNIUM SERIES")
313 FORMAT(3X,"CHAIN 3 - URANIUM SERIES")
314 FORMAT(3X,"CHAIN 4 - ACTINIUM SERIES")
315 FORMAT(3X,"ACTIVATION PRODUCTS")
316 FORMAT(3X,I3,3X,I3,3X,5(1PE10.2,5X),10X,"TIME =",1PE10.2)
317 FORMAT(17X,A8,16X,4(1PE10.2,6X),1PE10.2,4X,1PE10.2)
318 FORMAT(10X,3(1PE10.2,10X))
319 FORMAT(1H1,7X,"TIME",10X,"RECHARGE",10X,"TOTAL CURIES")
320 FORMAT(/1X,"==========================================="/)
321 FORMAT(1X,"***********")
322 FORMAT(//2X,"TIME",2X,"TOTAL CURIES",2X,"DIS EPA RATIO",
   *2X," AE-TOTAL ",2X,"AE-EPA RATIO",2X," C-14 AE ",2X,
   *" TC-99 AE ",2X," I-129 AE ",2X," NI-59 AE ",2X,
   *" CS-135 AE ",2X," SN-126 AE"/)
323 FORMAT(11(1PE10.2,2X))
325 FORMAT(99X,"RECHARGE RATE =",1PE10.2)
326 FORMAT(/,5X,"TIME",4X,
   *" ZR-93 AE ",2X," SR-90 AE ",2X," CS-137 AE",
   *2X," CM-244 AE",2X," PU-240 AE",2X," U-236 AE ",2X,
   *" TH-232 AE",2X," CM-245 AE",2X," PU-241 AE",2X,
   *" AM-241 AE"/)
327 FORMAT(/,5X,"TIME",4X," NP-237 AE",2X,
   *" U-233 AE ",2X," TH-229 AE",2X," RA-225 AE",
   *2X," CM-246 AE",2X," AM-242 AE",2X," CM-242 AE",2X,
   *" PU-242 AE",2X," PU-238 AE",2X," U-238 AE "/)
328 FORMAT(/,5X,"TIME",4X," U-234 AE",2X," TH-230 AE",2X,
   *" RA-226 AE",2X," PB-210 AE",2X," AM-243 AE",
   *2X," NP-239 AE",2X," PU-239 AE",2X," U-235 AE ",2X
   *"PA-231 AE",2X,"AECID"/)
9999 STOP
     END
     SUBROUTINE BAT(NCHNS,AL,T,NEC,CONI,TM21,TM31,TM41,TM32,TM42,
    *TM43,TM51,TM52,TM53,TM54,CONN)
     DIMENSION AL(5,14),TM21(14),TM31(14),TM41(14),TM32(14),
    *TM43(14),TM42(14),EXT(5,14),NEC(14),CONI(5,14),CONN(5,14),
    *TM51(14),TM52(14),TM53(14),TM54(14)
     DO 2 I=1,NCHNS
     N=NEC(I)
     DO 2 J=1,N
     CONN(J,I)=0.
     Z=-AL(J,I)*T
     IF(Z.GT.-1.E100)GO TO 5
     EXT(J,I)=0.
     GO TO 6
5    EXT(J,I)=EXP(Z)
6    CONTINUE
2    CONTINUE
     DO 3 I=1,NCHNS
     C1=CONI(1,I)
     C2=CONI(2,I)
     C3=CONI(3,I)
     C4=CONI(4,I)
     C5=CONI(5,I)
     N=NEC(I)
     CONN(1,I)=C1*EXT(1,I)
      IF(N.EQ.1)GO TO 4
     X=AL(1,I)*TM21(I)*C1
     Y=-X+C2
     CONN(2,I)=X*EXT(1,I)+Y*EXT(2,I)
     IF(N.EQ.2)GO TO 4
     X=AL(1,I)*AL(2,I)*C1
     X1=X*TM21(I)*TM31(I)*EXT(1,I)
     Y=-X*TM21(I)*TM32(I)+AL(2,I)*C2*TM32(I)
     Y1=Y*EXT(2,I)
     Z=X*TM31(I)*TM32(I)-AL(2,I)*C2*TM32(I)+C3
     Z1=Z*EXT(3,I)
     CONN(3,I)=X1+Y1+Z1
     IF(N.EQ.3)GO TO 4
     X=AL(1,I)*AL(2,I)*AL(3,I)*C1
      Y=AL(2,I)*AL(3,I)*C2
     X1=X*TM21(I)*TM31(I)*TM41(I)*EXT(1,I)
     Y1=-X*TM21(I)*TM32(I)*TM42(I)
     Y1=Y1+Y*TM32(I)*TM42(I)
     Y1=Y1*EXT(2,I)
     Z1=X*TM31(I)*TM32(I)*TM43(I)
     Z1=Z1-Y*TM32(I)*TM43(I)
     Z1=Z1+C3*AL(3,I)*TM43(I)
     Z1=Z1*EXT(3,I)
     W1=-X*TM41(I)*TM42(I)*TM43(I)
     W1=W1+Y*TM42(I)*TM43(I)
     W1=W1-AL(3,I)*C3*TM43(I)+C4
     W1=W1*EXT(4,I)
     CONN(4,I)=X1+Y1+Z1+W1
     IF(N.EQ.4)GO TO 4
     A1=AL(1,I)*AL(2,I)*AL(3,I)*AL(4,I)*C1
     A2=AL(2,I)*AL(3,I)*AL(4,I)*C2
     A3=AL(3,I)*AL(4,I)*C3
      U=A1*TM21(I)*TM31(I)*TM41(I)*TM51(I)
     U=U*EXT(1,I)
     V=-A1*TM21(I)*TM32(I)*TM42(I)*TM52(I)
     V=V+A2*TM32(I)*TM42(I)*TM52(I)
     V=V*EXT(2,I)
     W=A1*TM31(I)*TM32(I)*TM43(I)*TM53(I)
     W=W-A2*TM32(I)*TM43(I)*TM53(I)
     W=W+A3*TM43(I)*TM53(I)
     W=W*EXT(3,I)
     X=-A1*TM41(I)*TM42(I)*TM43(I)*TM54(I)
     X=X+A2*TM42(I)*TM43(I)*TM54(I)
     X=X-A3*TM43(I)*TM54(I)
     X=X+AL(4,I)*C4*TM54(I)
     X=X*EXT(4,I)
     Y=A1*TM51(I)*TM52(I)*TM53(I)*TM54(I)
     Y=Y-A2*TM52(I)*TM53(I)*TM54(I)
     Y=Y+A3*TM53(I)*TM54(I)
     Y=Y-TM54(I)*AL(4,I)*C4
      Y=(Y+C5)*EXT(5,I)
     CONN(5,I)=U+V+W+X+Y
4    CONTINUE
3    CONTINUE
      RETURN
      END
```

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DOE/RW-0074

Nuclear Waste Policy Act
(Section 112)

A Multiattribute Utility Analysis of Sites Nominated For Characterization For The First Radioactive-Waste Repository — A Decision-Aiding Methodology

May 1986

U.S. Department of Energy
Office of Civilian Radioactive Waste Management

Item # 2

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DOE/RW-0074

Nuclear Waste Policy Act
(Section 112)

A Multiattribute Utility Analysis of Sites Nominated For Characterization For The First Radioactive-Waste Repository— A Decision-Aiding Methodology

May 1986

U.S. Department of Energy
Office of Civilian Radioactive Waste Management
Washington, DC 20585

ERRATA

Page v (Table of Contents): title of Section 3.5.3 should read "Specification of the multiattribute utility function."

Page 5-10, Figure 5-7: the arrow labeled "Hanford" should be extended to the next curve.

Page 5-10, Figure 5-7: the labels for the scaling factors on the abscissa should be reversed; that is, the first row of scaling-factor values should be labeled "k_{pre}" and the second row should be labeled "k_{post}."

FOREWORD

In December 1984, the Department of Energy (DOE) published draft environmental assessments (EAs) to support the proposed nomination of five sites and the recommendation of three sites for characterization for the first radioactive-waste repository. A chapter common to all the draft EAs (Chapter 7) presented rankings of the five sites against the postclosure and the preclosure technical siting guidelines. To determine which three sites appeared most favorable for recommendation for characterization, three simple quantitative methods were used to aggregate the rankings assigned to each site for the various technical guidelines. In response to numerous comments on the methods, the DOE has undertaken a formal application of one of them (hereafter referred to as the decision-aiding methodology) for the purpose of obtaining a more rigorous evaluation of the nominated sites.

The application of the revised methodology is described in this report. The method of analysis is known as multiattribute utility analysis; it is a tool for providing insights as to which sites are preferable and why. The decision-aiding methodology accounts for all the fundamental considerations specified by the siting guidelines and uses as source information the data and evaluations reported or referenced in the EAs. It explicitly addresses the uncertainties and value judgments that are part of all siting problems. Furthermore, all scientific and value judgments are made explicit for the reviewer. An independent review of the application of the decision-aiding methodology has been conducted by the Board on Radioactive Waste Management of the National Academy of Sciences; the comments of the Board are included as an appendix to this report.

In spite of its advantages, the formal analysis cannot address every aspect of the site-recommendation decision and thus its results will not form the sole basis for that decision. The site-recommendation decision is analogous to a portfolio-selection problem because the DOE is not choosing a single site for repository development; rather, the DOE must choose, from a suite of five well-qualified sites, three sites for site characterization. Combinations of three sites possess properties that cannot be attributed to individual sites, such as diversity of geohydrologic settings and rock types. Thus, the three sites indicated as most preferable by the multiattribute utility analysis reported here do not necessarily constitute the most preferred combination when these portfolio effects are taken into account. The relative advantages of other combinations of three sites as portfolios together with other information the Secretary of Energy believes is important to making the decision are examined in a separate report.

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Chapter 1

BACKGROUND AND INTRODUCTION

1.1 BACKGROUND INFORMATION

The Department of Energy (DOE), pursuant to the Atomic Energy Act of 1954 as amended, the Energy Reorganization Act of 1974, the Department of Energy Organization Act of 1977, and the Nuclear Waste Policy Act of 1982 (the Act), has the responsibility to provide for the disposal of high-level radioactive waste and spent nuclear fuel.* The DOE selected mined geologic repositories as the preferred means for the disposal of commercially generated high-level radioactive waste and spent fuel (Federal Register, Vol. 46, p. 26677, May 14, 1981) after evaluating various means for the disposal of these materials and issuing an environmental impact statement. To carry out this decision, the DOE has been conducting research and development and performing siting studies.

The Act established a process and schedule for siting two geologic repositories by integrating the then-existing DOE siting program into its requirements and procedures. As explained later in this chapter, the Act requires the Secretary of Energy to nominate not fewer than five sites as suitable for site characterization and subsequently to recommend three of the nominated sites to the President as candidate sites for characterization. Site characterization will involve the collection of detailed information on the geologic, hydrologic, and other characteristics of the site that determine compliance with the requirements of the Environmental Protection Agency (EPA) and the Nuclear Regulatory Commission (NRC). It will involve the construction of exploratory shafts to the depth at which a repository would be built and in-situ testing. In parallel with these subsurface investigations, the DOE will collect information on the demographic, socioeconomic, and ecological characteristics of the affected areas containing the sites approved for site characterization. These subsurface and surface investigations are expected to cost upward of 500 million dollars per site.

This report presents a formal analysis of the five sites nominated as suitable for characterization for the first repository; the analysis is based on the information contained or referenced in the environmental assessments that accompany the site nominations (DOE, 1986a-e). It is intended to aid in

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*High-level radioactive waste means (1) the highly radioactive material resulting from the reprocessing of spent nuclear fuel, including liquid waste produced directly in reprocessing and any solid material derived from such liquid waste that contains fission products in sufficient concentrations and (2) other highly radioactive material that the Nuclear Regulatory Commission, consistent with existing law, determines by rule requires permanent isolation. For convenience, the terms "radioactive waste" and "waste" are used for both spent fuel and high-level radioactive waste.

the site-recommendation decision by providing insights into the comparative advantages and disadvantages of each site. Because no formal analysis can account for all the factors important to a decision as complex as recommending sites for characterization, this study will not form the sole basis for that decision. To help the reader understand the context of the formal study and of subsequent decisions, the remainder of this chapter presents additional background information on the geologic repository concept, the Act, and the DOE siting process, before and after the passage of the Act.

1.1.1 THE GEOLOGIC REPOSITORY CONCEPT

A geologic repository will be developed much like a large mine. Shafts will be constructed to allow for the removal of excavated material and to permit the construction of tunnels and disposal rooms at some depth between 1000 and 4000 feet underground. Other shafts will be constructed to allow for the transfer of waste. Surface facilities will be provided for receiving and preparing the waste for emplacement underground. The surface and underground facilities will occupy about 400 and 2000 acres of land, respectively. When the repository has been filled to capacity and its expected long-term performance has been shown to be satisfactory, the surface facilities will be decommissioned and all shafts and boreholes will be backfilled and permanently sealed.

A repository can be viewed as a system of multiple barriers, both natural and engineered, that act together to contain and isolate the waste. The engineered barriers include the waste package, the underground facility, and shaft and tunnel backfill materials. The waste package consists of the waste form, either spent nuclear fuel or solidified high-level waste, a metal containers, and perhaps a specially designed backfill material to separate the waste containers from the host rock. The waste package contributes to long-term isolation by delaying eventual contact between the waste and ground water. The underground facility consists of underground openings and backfill materials not associated with the waste package. These barriers further limit any ground-water circulation around the waste packages and impede the subsequent transport of radionuclides into the environment.

The geologic, hydrologic, and geochemical features of the site constitute natural barriers to long-term movement of radionuclides to the accessible environment. These natural barriers provide waste isolation by impeding radionuclide transport through the ground-water system to the accessible environment and possess characteristics that reduce the potential for human interference in the future.

Although the DOE plans to use engineered barriers--as required by both the NRC in 10 CFR Part 60 (NRC, 1983), and the EPA in 40 CFR Part 191 (EPA, 1985)--primary reliance is placed on the natural barriers for waste isolation. Therefore, in evaluating the suitability of sites, the use of an engineered-barrier system will be considered to the extent necessary to meet the performance requirements specified by the NRC and the EPA but will not be relied on to compensate for major deficiencies in the natural barriers.

1.1.2 THE NUCLEAR WASTE POLICY ACT OF 1982

The search for suitable repository sites has been under way for about 10 years, although preliminary screening began in the mid 1950s. With the passage of the Act, a specific process for siting and licensing repositories was established. Through provisions for consultation and cooperation as well as financial assistance, the Act also established a prominent role in the siting process for potential host States, affected Indian Tribes, and the public. To pay the costs of geologic disposal, the Act provides for a Nuclear Waste Fund through which commercial electric utility companies are charged a fee that is based on the amount of electricity they produce in nuclear power plants. The DOE's strategy for implementing the provisions of the Act is discussed in detail in the Mission Plan for the Civilian Radioactive Waste Management Program (DOE, 1985).

In February 1983, the DOE carried out the first requirement of the Act by formally identifying nine potentially acceptable sites for the first repository in the following locations (the host rock of each site is shown in parentheses):

1. Vacherie dome, Louisiana (salt dome)
2. Cypress Creek dome, Mississippi (salt dome)
3. Richton dome, Mississippi (salt dome)
4. Yucca Mountain, Nevada (tuff)
5. Deaf Smith County, Texas (bedded salt)
6. Swisher County, Texas (bedded salt)
7. Davis Canyon, Utah (bedded salt)
8. Lavender Canyon, Utah (bedded salt)
9. Reference repository location, Hanford Site, Washington (basalt flows)

The location of these sites in their host States is shown in Figure 1-1.

The Act further requires the DOE to issue general guidelines to be used in determining the suitability of these potentially acceptable sites. In February 1983, the DOE published draft general guidelines for siting repositories (the guidelines). The DOE revised the guidelines after receiving extensive comments from the NRC, the States, Indian Tribes, other Federal agencies, and the public. The NRC concurred with the revised guidelines in June 1984, and the final guidelines were promulgated in December 1984 (DOE, 1984a).

The Act requires that, after the guidelines are issued, the DOE nominate at least five sites as suitable for site characterization. Section 112(b)(1)(E) of the Act requires that an environmental assessment be prepared for each site proposed for nomination as suitable for characterization. The contents of the environmental assessments are described in a later section of this chapter. The DOE must then recommend not fewer than three of those sites for characterization as candidate sites for the first repository.

During site characterization, the DOE will construct exploratory shafts for underground testing to determine whether geologic conditions will allow the construction of a repository that will safely isolate radioactive waste. The Act requires the DOE to prepare site-characterization plans for NRC review. After site characterization and an environmental impact statement are completed, the DOE will recommend one of the characterized sites for development as a repository.

Figure 1-1. Potentially acceptable sites for the first repository.

1.2 SUMMARY OF THE OVERALL SITING PROCESS

In seeking sites for geologic repositories, the DOE divides the siting process into the following phases: (1) screening, (2) site nomination, (3) site recommendation for characterization, (4) site characterization, and (5) site selection (recommendation for development as a repository). This section describes the site-screening process, which led to the identification of the nine potentially acceptable sites for the first repository listed in Section 1.1, and reviews how the process of site nomination and recommendation is implemented under the guidelines.

1.2.1 SITE SCREENING

During the screening phase, the DOE identified potential sites for characterization. This phase provides the information needed for judging which of these sites appear to justify the investment necessary to characterize them. Screening may consist of as many as four stages, each of which progressively narrows the study area to a smaller land unit. These stages are as follows:

1. A survey of <u>geologic provinces</u>, narrowing to <u>regions</u>. Regions are generally smaller than provinces but may extend across several States and occupy tens of thousands of square miles.

2. A survey of the <u>regions</u>, narrowing to <u>areas</u> that encompass hundreds to thousands of square miles. The regional screening phase was completed with the publication of regional characterization reports and area-recommendation reports.

3. A survey of the <u>areas</u>, narrowing to <u>locations</u> that usually occupy an area smaller than 100 square miles. This phase was completed with the publication of location-recommendation reports for bedded salt and site-recommendation reports for salt domes.

4. A survey of the <u>locations</u>, narrowing to <u>sites</u>, which are generally smaller than 10 square miles. While a location may be large enough to contain several sites, only one or two potential sites are usually identified in a particular location.

During each screening stage, the DOE identified as many potentially suitable land units as were judged to be necessary for an adequate sample to be studied in the next stage. Only the regions and areas believed most likely to contain suitable sites received further study; the evaluation of all others was deferred.

Data for comparing regions, areas, and locations became increasingly detailed as progressively smaller land units were considered and as exploration and testing were concentrated on them. National, province, and regional surveys were based on potential host rocks, published geologic maps, maps of earthquake epicenters, land use, available geohydrologic information, and other information available in the open literature. Area and location surveys require more thorough investigations, which included field exploration and testing and the drilling of boreholes to investigate subsurface hydrologic, stratigraphic, and geochemical conditions. The field studies were supported by laboratory studies that focused on both the waste-isolation and the engineering characteristics of potential host rocks.

The bedded-salt sites in Texas and Utah were identified through the general siting process described above, beginning with national surveys and progressively narrowing to locations and sites. The salt domes were selected by a screening that began with more than 200 domes and ended with the three sites identified as potentially acceptable.

Screening for sites in basalt and tuff was initiated when the DOE began to search for suitable repository sites on some Federal lands where radioactive materials were already present. This approach was recommended by the Comptroller General of the United States (1979). Although land use was the beginning basis for this screening of Federal lands, the subsequent progression to smaller land units was based primarily on evaluations of geologic and hydrologic suitability. The studies began at roughly the area stage.

The technical factors used to guide site-screening decisions have evolved throughout the site-search period and are specified in a number of published documents (Brunton and McClain, 1977; DOE, 1981; DOE, 1982a; International Atomic Energy Agency, 1977; NAS-NRC, 1978).

The sections that follow summarize how the DOE applied the screening process outlined above to determine that the nine sites listed in Section 1.1.2 are potentially acceptable. Section 2.2 of each environmental assessment discusses in detail how the DOE conducted site screening in specific geohydrologic settings.

1.2.2 SALT SITES

Salt was first recommended as a potentially suitable host rock for waste disposal in 1955, after the National Academy of Sciences-National Research Council evaluated many options (NAS-NRC, 1957). This recommendation was reaffirmed in subsequent reports (e.g., American Physical Society, 1978; NAS-NRC, 1970). Rock salt, which occurs both as bedded salt and in salt domes, has several characteristics that are favorable for isolating radioactive waste, including the following:

- Salt deposits that are sufficiently deep, thick, and laterally extensive to accommodate a repository are widespread in the United States and generally occur in areas of low seismic and tectonic activity.

- Many salt bodies have remained undisturbed and dry for tens of millions to several hundred million years.

- Because of its high thermal conductivity in comparison with other rock types, rock salt has the ability to efficiently dissipate the heat that will be generated by the waste.

- Salt deforms in a relatively plastic manner under high confining pressure so that fractures that might develop at repository depth would tend to close and seal themselves.

Screening of the entire United States in the 1960s and 1970s resulted in the identification of four large regions that are underlain by rock salt of sufficient depth and thickness to accommodate a repository and represent diverse geohydrologic conditions (Johnson and Gonzales, 1978; Pierce and Rich, 1962). The four regions are as follows:

- Bedded salt in the Michigan and Appalachian Basins of southern Michigan, northeastern Ohio, western Pennsylvania, and western New York (also called the "Salina Basin").
- Salt domes within a large part of the Gulf Coastal Plain in Texas, Louisiana, and Mississippi.
- Bedded salt in the Permian Basin of southwestern Kansas, western Oklahoma, northwestern Texas, and eastern New Mexico.
- Bedded salt in the Paradox Basin of southeastern Utah, southwestern Colorado, and northernmost Arizona and New Mexico.

This screening at the national level served as the basis for all subsequent screening in salt. After proceeding to the location phase, further screening of the Salina Basin salt deposits was deferred, and the last three regions were selected for further study.

1.2.2.1 Salt domes in the Gulf Coast salt-dome basin of Mississippi and Louisiana

There are more than 500 salt domes in the Gulf Coast salt-dome basin of Texas, Louisiana, Mississippi, and areas offshore from these States. An initial screening by the U.S. Geological Survey (USGS) eliminated all offshore domes. The application of this criterion eliminated about half the domes. The USGS also evaluated the remaining 263 onshore domes and identified 36 as being potentially acceptable for a repository and another 89 that were worthy of further study (Anderson et al., 1973). The USGS screening factors were depth to the top of the dome and present use for gas storage or hydrocarbon production.

The DOE and its predecessor agencies conducted regional studies of 125 salt domes identified in the earlier USGS screening mentioned above. All but 11 of the domes were eliminated on the basis of three screening factors: depth to salt, lateral extent of the domes, and potential for competing uses (NUS Corporation, 1978; ONWI, 1979). Three of the 11 domes were removed from consideration on the basis of environmental factors, and a fourth was eliminated because solution mining at the site contributed to a collapse of strata above the dome.

Area-characterization studies were completed for the seven remaining dome areas: Rayburn's and Vacherie domes in Louisiana; Cypress Creek, Lampton, and Richton domes in Mississippi; and Keechi and Oakwood domes in Texas. The geologic field work conducted during this phase included the drilling of deep holes to collect rock cores for laboratory tests of their properties, and geophysical surveys to determine the underlying rock structures. The area environmental studies included descriptions of the plant and animal communities, surface- and ground-water systems, weather conditions, land use, and socioeconomic characteristics. An evaluation of the seven domes on the basis of the DOE's criteria is summarized in a location-recommendation report (ONWI, 1982a).

In the area-characterization studies, a repository-size criterion was chosen that was more restrictive than the one used in earlier screening studies. The application of this stricter criterion resulted in the elimination of Keechi, Rayburn's, and Lampton domes (ONWI, 1982a). Thus, at the conclusion of area characterization, the Vacherie, Richton, Oakwood, and Cypress Creek domes were recommended for further screening. After further review of the area-characterization studies, the Oakwood dome was deferred from further consideration because of uncertainties raised by large-scale petroleum exploration.

In accordance with the Act, the DOE identified the Cypress Creek, Richton, and Vacherie domes as potentially acceptable sites in February 1983.

1.2.2.2 Bedded salt in the Paradox Basin

Screening criteria were developed for the bedded salt of the Paradox Basin, which the USGS had identified as worthy of further investigation (Pierce and Rich, 1962). The following factors were applied to identify areas for further investigation (Brunton and McClain, 1977; DOE, 1981; NUS Corporation, 1978): depth and thickness of salt, mapped faults, other evidence of recent geologic instability, zones of ground-water discharge, significant resources, and potential for flooding. The results of this screening were integrated with screening for environmental and socioeconomic factors, such as proximity to urban areas and the presence of certain dedicated lands. On the basis of this regional screening, four areas were recommended for further study: Gibson Dome, Elk Ridge, Lisbon Valley, and Salt Valley (ONWI, 1982b).

The screening factors used to identify potentially favorable locations within the four areas were the depth to salt, the thickness of salt, proximity to faults and boreholes, and proximity to the boundaries of dedicated lands (ONWI, 1982c). These screening factors were judged to have the strongest potential for differentiating possible locations within the areas.

Salt Valley and Lisbon Valley were both deferred from further consideration because all areas with an adequate depth to salt were too close to zones of mapped surface faults and, for Lisbon Valley, because of existing boreholes (ONWI, 1982c).

Application of the screening factors to the Gibson Dome showed a location of 57 square miles near the center of the area that contained appropriately deep and thick salt deposits and was sufficiently far from faults or exploration boreholes that would make a site unsuitable. It also appeared to be sufficiently distant from dedicated lands. This location is referred to as the Gibson Dome location. The Elk Ridge area contained one location of about 6 square miles and several smaller ones, each less than 3 square miles, that met the screening criteria (ONWI, 1982c). The smaller locations were not large enough for a repository and were therefore excluded from further consideration. The larger location was designated the Elk Ridge location.

Further comparisons of the Gibson Dome and Elk Ridge locations were made on the basis of more-refined criteria that discriminated between them. The thickness of salt, the thickness of shale above and below the depth of a repository, and the minimum distance to salt-dissolution features were considered the most critical geologic discriminators. Archaeological sensitivity and site accessibility were considered the most important environmental factors. The Gibson Dome location was judged to be superior to the Elk Ridge location in terms of the number and relative importance of favorable factors and was selected as the preferred location (ONWI, 1982c).

During 1982 and 1983 three sites were identified for further evaluation: Davis Canyon, Lavender Canyon, and Harts Draw. Since much of the intrinsic value of southeastern Utah stems from its scenic and aesthetic character, a study of visual aesthetics was performed to evaluate the three sites (Bechtel Group Inc., 1983). Harts Draw was found to be less desirable than the sites at Davis Canyon and Lavender Canyon because it affords a greater total area of visibility, and it was eliminated from further consideration. In February 1983, Davis Canyon and Lavender Canyon were identified as potentially acceptable sites.

1.2.2.3 Bedded salt in the Permian Basin

In 1976, the Permian bedded-salt deposits in the Texas Panhandle and western Oklahoma that were identified in the USGS study (Pierce and Rich, 1962) were evaluated to determine whether they contained any areas that might be suitable for waste disposal (Johnson, 1976). Since the parts of the Permian Basin in western Kansas and Texas and in eastern Colorado and New Mexico had been screened as part of an earlier site evaluation for the Waste Isolation Pilot Plant (WIPP), this screening focused on five subbasins: the Anadarko, Palo Duro, Dalhart, Midland, and Delaware Basins. All contain salt beds of adequate thickness and depth. A site had already previously been selected in the Delaware Basin as a site for the WIPP facility for radioactive defense wastes (DOE, 1980a). The Palo Duro and the Dalhart Basins had far less potential for oil and gas production and have not been penetrated as extensively by drilling as have the Anadarko and the Midland Basins. Therefore, the Palo Duro and the Dalhart Basins were judged to be preferable to the other three and were recommended for further studies at the area stage (ONWI, 1983a). These two basins rated higher on six major screening factors: the depth and thickness of salt, seismicity, known oil and gas deposits, the presence of exploratory boreholes, and evidence of salt dissolution.

More-detailed geologic and environmental studies of the Palo Duro and the Dalhart Basins began in 1977, and screening criteria were developed to define locations with favorable characteristics. Six locations in parts of Deaf Smith, Swisher, Oldham, Briscoe, Armstrong, Randall, and Potter Counties, Texas, met the screening criteria. A second set of criteria was then applied to further differentiate among the six locations. These criteria reflected siting factors related to geomorphology, the presence of natural resources, flexibility in repository siting at specific locations, the number of boreholes at each location, population density, and land-use conflicts. After applying these criteria, the DOE decided to focus on the two locations that had the greatest likelihood of containing a suitable site, one in northeastern Deaf Smith and southeastern Oldham Counties and one in northcentral Swisher County. All other locations in the Palo Duro Basin were deferred from further consideration (ONWI, 1983b). In February 1983, the DOE identified parts of Deaf Smith County and Swisher County as potentially acceptable sites and subsequently narrowed the size of the two sites to be considered at each location (DOE, 1984b).

1.2.3 SITES IN BASALT AND TUFF

In 1977, the waste-disposal program was expanded to consider previous land use as an alternative basis for site screening. This approach considered the advantages of locating a repository on land already withdrawn and committed to long-term institutional control. Because both the Hanford Site and the Nevada Test Site are dedicated to nuclear operations, will remain under Federal control, and are underlain by potentially suitable rocks, screening was initiated in these two areas.

1.2.3.1 Basalt in the Pasco Basin, Washington

The DOE and its predecessor agencies have investigated the geologic and hydrologic characteristics of the Pasco Basin since 1977 as a continuation of studies conducted for the defense-waste-management program between 1968 and 1972 (Gephart et al., 1979; Myers et al., 1979). These investigations showed that the thick formations of basalt lava in the Pasco Basin are suitable for further investigation as a geologic repository for the following reasons:

- Several basalt flows more than 2100 feet below ground apparently are thick enough to accommodate a geologic repository.
- The slow rate of deformation of the basalt ensures the long-term integrity of a repository at the Hanford Site. Also, there are synclines where structural deformation appears to be limited.
- The potential for renewed volcanism at the Hanford Site is very low.
- The likely geochemical reactions between the basalt rock, ground water, and the waste are favorable for long-term isolation.

The Pasco Basin was selected for screening to provide a broader scope from which to study processes that might affect the Hanford Site and to determine whether there are any obviously superior sites in the natural region outside, but contiguous with, the Hanford Site (Woodward-Clyde Consultants, 1980, 1981).

The first step in screening was to define the candidate area. The considerations used at this step were fault rupture, ground motion, aircraft traffic, ground transportation, operational radiation releases from nuclear facilities at the Hanford Site, protected ecological areas, culturally important areas, and site-preparation costs. A candidate area was identified that included the central part of the Hanford Site and adjacent land east of the Hanford Site.

The second step in the screening was to define subareas (locations). The siting factors used in this screening step were fault rupture, flooding, ground failure, erosion, the presence of hazardous facilities, induced seismicity, and site-preparation costs. This step eliminated approximately half the candidate area.

Locations were identified through an evaluation of the subareas inside and adjacent to the Hanford Site. On the basis of land use, hydrologic conditions, and bedrock dip, subareas outside the Hanford Site were eliminated because they were not obviously superior to those found within the Hanford Site. After eliminating these subareas, five locations were identified within the boundaries of the Hanford Site.

The identification of candidate sites from among the five locations was based on an evaluation of 23 parameters (Rockwell 1980, 1981). Nine candidate sites were identified, seven of which lay in the Cold Creek Syncline, a major structural feature of the Pasco Basin. This syncline was selected partly because it is not as extensively deformed as nearby anticlines and is underlain by relatively horizontal strata. Since the other two sites were not technically superior to those in the Cold Creek Syncline and were closer to the Columbia River, they were removed from further study. To avoid some geophysical anomalies of uncertain source, three other sites were identified; they were largely superimposed on parts of the original seven sites in the Cold Creek Syncline (Myers and Price, 1981).

Since preliminary evaluations of the resulting 10 partly overlapping candidate sites indicated that the sites were too closely matched to be differentiated by routine ranking, a formal decision analysis was used to identify the best site (Rockwell, 1980). Decision criteria were derived from the following siting factors: bedrock fractures and faults, lineaments, potential earthquake sources, ground-water-travel times, contaminated soil, surface facilities, thickness of the proposed repository horizon, repetitive occurrence of columnar-jointed zones (colonnades) within the host flow, natural vegetative communities, unique microhabitats, and special species. The analysis showed that two approximately coincident sites rated higher than the other sites. These two sites were combined and designated "the reference repository location." In February 1983, the DOE identified the reference repository location as a potentially acceptable site.

1.2.3.2 <u>Tuff in the Southern Great Basin, Nevada</u>

At the same time that the DOE was considering the Nevada Test Site (NTS) on the basis of land use, the USGS proposed that the NTS be considered for investigation as a potential repository site for a variety of geotechnical reasons, including the following:

- Southern Nevada is characterized by closed hydrologic basins. This means that ground water does not discharge into rivers that flow to major bodies of surface water.

- Long flow paths occur between potential repository locations and ground-water discharge points.

- Many of the rocks occurring at the NTS have geochemical characteristics that are favorable for waste isolation.

- The NTS is located in an arid region (6 to 8 inches per year of rainfall). With the very low rate of recharge, the amount of moving ground water is also low, especially in the unsaturated zone.

In 1977, the geologic medium of prime interest at the NTS was argillite (a clay-rich rock), which occurs under the Syncline Ridge, near the center of the NTS. Geologic investigations and exploratory drilling there revealed a complex geologic structure in the center of the area being considered (Hoover and Morrison, 1980; Ponce and Hanna, 1982). It was decided in July 1978 that the geologic complexity of the area would make characterization prohibitively difficult, and further evaluation was deferred.

A question then arose concerning the compatibility of a repository with the testing of nuclear weapons—the primary purpose of the NTS. A task group formed to evaluate this issue determined in 1978 that a repository located in other than the southwestern portion of the NTS might be incompatible with weapons testing. At that time the program refocused on the area in and around the southwestern corner of the NTS, which subsequently was named the Nevada Research and Development Area (NRDA). The entire area then being evaluated included land controlled by the Bureau of Land Management west and south of the NRDA and a portion of the Nellis Air Force Range west of the NRDA.

In August 1978, a preliminary list of potential sites in and near the southwestern part of the NTS was compiled. The areas initially considered included Calico Hills, Skull Mountain, Wahmonie, Yucca Mountain, and Jackass Flats. Of these five areas, Calico Hills, Wahmonie, and Yucca Mountain were considered the most attractive locations for preliminary borings and geophysical testing.

The Calico Hills location was known to contain argillite. It was of particular interest because a geophysical survey showed that granite might occur approximately 1600 feet below the surface. The first exploratory hole for waste-disposal studies at the NRDA was drilled in 1978 in an attempt to confirm the existence of granite beneath the Calico Hills. Drilling was discontinued at a depth of 3000 feet without reaching granite (Maldonado et al., 1979). Additional geophysical surveys indicated that the argillite at Calico Hills is probably very complex structurally, comparable with that at Syncline Ridge (Hoover et al., 1982). Because the granite was considered too deep and the argillite appeared too complex, further consideration of the Calico Hills was suspended in the spring of 1979.

Concurrent with drilling at Calico Hills, geophysical studies and surface mapping conducted at Wahmonie indicated that the granite there may not be large enough for a repository, that any granite within reasonable depths may contain deposits of precious metals, and that faults in the rock may allow vertical movement of ground water (Hoover et al., 1982; Smith et al., 1981). For these reasons, Wahmonie was eliminated from consideration in the spring of 1979.

Surface mapping of Yucca Mountain indicated the existence of a generally undisturbed structural block large enough for a repository. In 1978, the first exploratory hole drilled at Yucca Mountain confirmed the presence of thick, highly sorptive units of tuff (Spengler et al., 1979). Because tuff previously had not been considered as a potential host rock for a repository, a presentation was made to the National Academy of Sciences (NAS) Committee for Radioactive Waste Management in September 1978 to solicit its views on the potential advantages and disadvantages of tuff as a repository host rock. The NAS committee supported the concept of investigating tuff as a potential host rock (DOE, 1980b), and in a letter dated February 5, 1982, to the DOE Nevada Operations Office, the USGS pointed out the considerable advantages of locating a repository in the unsaturated zone. After comparing the results of preliminary exploration at Calico Hills, Wahmonie, and Yucca Mountain, the USGS recommended that attention be focused on Yucca Mountain. A technical peer-review group supported the DOE's decision to concentrate exploration efforts on the tuffs of Yucca Mountain (DOE, 1980b).

Because the foregoing process of selecting Yucca Mountain for early exploration was not highly structured, a more thorough, formal analysis was begun in 1980 to evaluate whether Yucca Mountain was indeed appropriate for further exploration. This analysis was conducted in a manner compatible with the area-to-location phase of site screening described in the national siting plan (DOE, 1982b), which was used by the DOE before the passage of the Act and the formulation of the guidelines. Details of the formal analysis are presented by Sinnock and Fernandez (1984). In brief, this formal decision analysis evaluated 15 potential locations and concluded that Yucca Mountain was indeed the preferred location. Several potentially suitable horizons were identified in the saturated and unsaturated zones. Therefore, the DOE identified Yucca Mountain as a potentially acceptable site in February 1983.

1.2.4 NOMINATION AND RECOMMENDATION OF SITES FOR CHARACTERIZATION

The preceding sections described the siting process from its beginning to the point where nine sites had been identified as being potentially acceptable. The next steps are mandated by the Act: the Secretary of Energy is to nominate at least five sites that are suitable for characterization and to recommend to the President not fewer than three of those sites for characterization as candidate sites for the first repository. The discussion that follows assumes some knowledge of the form and content of the DOE's siting guidelines. The reader unfamiliar with the guidelines is referred to Section 2.4 for a very brief description or to the guidelines themselves (DOE, 1984a) for a more detailed description.

The guidelines, in 10 CFR Part 960.3-2-2-2, require the DOE to implement the following six-part process in selecting sites for nomination as suitable for characterization from among the potentially acceptable sites:

1. Evaluate the potentially acceptable sites in terms of the disqualifying conditions specified in the guidelines.

2. Group all potentially acceptable sites according to their geohydrologic settings.

3. For the geohydrologic settings that contain more than one potentially acceptable site, select the preferred site on the basis of a comparative evaluation of all potentially acceptable sites in that setting.

4. Evaluate each preferred site within a geohydrologic setting and decide whether such site is suitable for the development of a repository under the qualifying condition of each guideline that does not require site characterization as a prerequisite for such evaluation.

5. Evaluate each preferred site within a geohydrologic setting and decide whether such site is suitable for site characterization under the qualifying condition of each guideline that requires characterization for evaluation of suitability for development as a repository.

6. Perform a reasonable comparative evaluation under each guideline of the sites proposed for nomination.

To document the process specified above, draft environmental assessments (EAs) were prepared for each of the nine sites identified as potentially acceptable (DOE, 1984c-g). The draft EAs, which also include the evaluations and descriptions specified by the Act, were issued for public comment in December 1984. The draft EAs proposed the following five sites (listed together with their corresponding geohydrologic setting) for nomination:

Geohydrologic setting	Site
Columbia Plateau	Reference repository location at the Hanford Site, Washington
Great Basin	Yucca Mountain, Nevada
Permian Basin	Deaf Smith County, Texas
Paradox Basin	Davis Canyon, Utah
Gulf Coastal Plain	Richton Dome, Mississippi

In addition to requesting written comments on the draft EAs, the DOE held a series of public briefings and hearings to receive oral comments. More than 20,000 comments were received, and among them were many comments on the three simple ranking methodologies presented in Chapter 7 of the draft EAs. The decisions to adopt a formal decision-analysis methodology and to prepare this separate report were made largely in response to the comments on the draft EAs. Also in response to public comments, the DOE requested that the Board on Radioactive Waste Management of the National Academy of Sciences conduct an independent review of the methodology.

On consideration of all of the comments on the draft EAs and the available evidence, evaluations, and resultant findings in the now final EAs (DOE, 1986a-e), the Secretary has determined that the five sites proposed for nomination in the draft EAs should be formally nominated. A notice specifying the sites so nominated and announcing the availability of the final EAs has been published in the Federal Register.

The screening and nomination processes have served the purpose of focusing closer scrutiny and more-rigorous evaluation on successively smaller areas. This progression to smaller land units was based primarily on evaluations of geologic and hydrologic suitability. With the completion of each step there has been greater basis for confidence that the remaining sites are technically sound. Thus, the selection of three sites to recommend for characterization is being made from among a set of five sites that have been nominated for consideration only after passing many increasingly stringent tests.

The site-recommendation decision must be based on the available geophysical, geologic, geochemical, and hydrologic data; other information; the evaluations and findings reported in the environmental assessments accompanying the nominations; and the diversity considerations specified below. The siting guidelines (10 CFR 960.3-2-3) specify that these data are to be applied in two distinct steps:

1. Determination of an initial order of preference for sites for characterization.

2. Determination of a final order of preference for sites for characterization, based on diversity of geohydrologic settings and diversity of rock types.

The formal analysis of sites presented herein is being used to determine the initial order of preference for sites for recommendation for characterization.

In determining a final order of preference of sites, the siting guidelines specify that, to the extent practicable, consideration be given to diversity of geohydrologic settings and of rock types. The diversity considerations arise from the premise that sites located in the same geohydrologic setting or in the same rock type may be subject to a common flaw. Also, because diverse geohydrologic settings imply differences in the nature of the accessible environment (e.g., a setting with surface-water bodies versus a desert environment), it is possible to consider whether the same quantity of radionuclides released from a repository at different sites might lead to drastically different consequences over the long term after repository closure (see Chapter 3).

The purpose of the process outlined above is to ensure that the sites recommended as candidate sites for characterization offer, on balance, the most advantageous combination of characteristics and conditions for the successful development of a repository at those sites.

1.3 ORGANIZATION OF THE REPORT

The remainder of this report (Chapters 2 through 5) presents the formal analysis of the comparative advantages and disadvantages of the five sites nominated as suitable for site characterization. Chapter 2 presents an overview of the formal decision-analysis technique known as multiattribute utility analysis. The role of the methodology and the process of its application are explained, its relationship to the DOE siting guidelines is discussed, and the basic steps in the methodology are outlined.

Chapters 3 and 4 present in summary form the postclosure and the preclosure analyses, respectively, of the five nominated sites. These analyses are based on the formal decision-aiding methodology. Results are presented for both a base case and for numerous sensitivity analyses.

Chapter 5 presents the composite analysis of the results presented in the two preceding chapters. These overall results form the basis for determining an initial order of preference for sites for characterization.

There are eight appendixes. Appendix A identifies the participants in the development and application of the the decision-aiding methodology. Appendixes B, C, and D contain detailed information on the postclosure analysis summarized in Chapter 3. Appendixes E and F contain detailed information on the preclosure analysis summarized in Chapter 4.

Appendix G presents background information on the multiattribute utility theory and detailed information on the assessed value tradeoffs and various other assumptions made in the application of the methodology.

Finally, Appendix H discusses the DOE's interactions with the Board on Radioactive Waste Management of the National Academy of Sciences on the development and application of the decision-aiding methodology. It also reproduces most of the DOE's correspondence with the Board.

For the convenience of the reader a glossary of terms is included.

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Chapter 2

THE DECISION-AIDING METHODOLOGY: OVERVIEW AND RELATIONSHIP TO THE SITING GUIDELINES

2.1 BACKGROUND AND INTRODUCTION

After selecting five sites for nomination as suitable for characterization, the DOE developed and applied a formal decision-analysis methodology as an aid in deciding which sites are preferred for recommendation for characterization. The methodology, which is based on multiattribute utility theory, involves an analysis that explicitly weighs the pros and cons of the nominated sites. Such an analysis can be a significant aid to decisionmakers; it can also help to objectively communicate the basis for the decision. Specifically, such an analysis can assist decisionmakers in three ways. It can--

- Provide information needed for judging which sites appear to justify the investment in characterizing them.
- Add credibility to the decision process.
- Provide a mechanism to facilitate constructive discussion and mediate potential conflict.

To achieve these goals the analysis should provide insights to help the decisionmakers understand which sites are more desirable than others and why. Furthermore, the analysis should illuminate which factors (e.g., data, professional judgments, value judgments, models) seem to be most crucial to the relative desirability of the sites. These suggest the sensitive issues to which more-careful analyses and time should be devoted. The decision process acquires credibility from the use of a sound logic and reasonable data, judgments and assumptions to provide understandable conclusions. By providing a model of the key factors in the decision problem, the analysis can be easily repeated to incorporate other viewpoints, and the implications of the differences can be easily identified and examined, thus facilitating discussion and the resolution of potential conflicts.

As mentioned, the analysis of the nominated sites is based on multiattribute utility theory. It has been applied to numerous other siting problems, such as power plants, dams, and refineries (see Keeney, 1980, for additional examples). The logical foundations of multiattribute utility analysis and the systematic procedures for its implementation have been well documented in the professional literature over the past 40 years (see, for example, von Neumann and Morgenstern, 1947; Savage, 1954; Pratt, Raiffa, and Schlaifer, 1964; Fishburn, 1970; and Keeney and Raiffa, 1976). The analysis also relies on the professional experience, judgment, data, and models that have been developed in the numerous disciplines involved in repository siting and in particular the evaluations of each nominated site against the siting guidelines (DOE, 1984), as reported in the environmental assessments that accompanied the nomination (DOE, 1986a-e).

The selection of multiattribute-utility theory for analyzing the site-recommendation problem is based on three advantages of the theory. First, it has an explicitly stated philosophical and logical basis for the methodology that is appropriate for the site-recommendation problem (see Merkhofer, 1986). Second, it separates the factual information and judgments about the performance and impacts of a repository at the various sites from value judgments about the desirability of those possible impacts. And third, both of these sets of information and judgments are made explicit for peer review and public review.

Crucial to multiattribute utility analysis are the sensitivity analyses that are conducted. The sensitivity analyses vary over reasonable ranges any of the inputs that could substantially affect the relative desirability, and hence the initial order of preference, of the nominated sites. Their purpose is to ascertain whether specific judgments or data are crucial to the conclusions drawn from the analysis. They thus suggest where further attention and effort should be focused.

In spite of its advantages, a formal analysis cannot address every aspect of the complex siting decision faced here. Excluded from the analysis, for example, is consideration of the advantages of a diversity of rock types. Because this or any methodology is capable of providing only a partial accounting of the many factors important to the site-recommendation decision, its results will not form the sole basis for that decision.

Regarding the design of the methodology, one additional point should be made; it is related to the concept of the diversity of rock types. The method of analysis used here evaluates the overall desirability of each nominated site, not the desirability of combinations of sites. The evaluation of all possible combinations of sites, each of the possible combinations being considered as an alternative, would require an extended, more-difficult form of analysis known as a "portfolio analysis." As explained by Edwards and Newman (1982), such sophistication is rarely used in portfolio problems. Instead, the more-common procedure is to evaluate the options (i.e., sites) by methods similar to the one described here and then to examine the resulting set of choices to determine their acceptability as a portfolio. This is exactly the procedure outlined in Section 1.2.4.

The sections that follow present a brief overview of the methodology (Section 2.2), explain the process by which it was implemented (Section 2.3), and discuss the relationship of the methodology to the DOE's siting guidelines (Section 2.4).

2.2 OVERVIEW OF THE ANALYSIS

The logic underlying multiattribute utility analysis is relatively straightforward, although the specific steps and the nomenclature may be unfamiliar to some readers. (A glossary is provided at the end of the report.) The basic premise is that the relative desirability of a site is measured by the extent to which siting objectives are achieved. The siting objectives are derived directly from the DOE's siting guidelines (see Section 2.4). The degree to which siting objectives are achieved is indicated by the performance and impacts predicted for a repository at the site. The performance and impacts are assessed on the basis of technical models, data, and professional judgment. The methodology is designed to aggregate these assessments in an appropriate and logical manner to provide an overall evaluation of the nominated sites.

The six basic steps of the methodology, as applied to the evaluation of sites, are the following:

1. Establish the objectives of repository siting and develop preclosure and postclosure performance measures for quantifying levels of performance with respect to these objectives.

2. For the postclosure analysis, specify a set of scenarios that, should they occur, might affect the performance of the repository system as represented by the postclosure-performance measures.

3. For each scenario, estimate postclosure performance with respect to each postclosure-performance measure. Estimate preclosure performance and impacts with respect to each preclosure-performance measure.

4. Assess the relative values of different levels of performance against each objective (i.e., assess a utility function over each performance measure) and assess value tradeoffs to integrate the achievement of different objectives into an overall utility function.

5. Using the overall utility function, aggregate impacts to obtain a composite score indicating the relative desirability of each site.

6. Perform sensitivity analyses to determine which models, data, technical judgments, and value judgments seem most significant for drawing insights from the analysis.

Each of the steps is reviewed in more detail below.

<u>Step 1: Establish Objectives and Develop Measures for Quantifying Levels of Performance</u>

A basic premise of the decision-aiding methodology is that the "goodness," or the utility, of a site is related to the extent to which that site achieves the various objectives of a geologic repository for radioactive waste. Thus, the first step in the application of the methodology is to explicitly define objectives. It is convenient to organize the objectives in a tree, or hierarchical, structure, as shown in Figure 2-1.

The overall objective is to minimize the adverse impacts of a repository. This objective is divided into "minimize adverse preclosure impacts" and "minimize adverse postclosure impacts." Because such objectives are too broad to be of practical value in distinguishing among sites, more-detailed lower-level objectives necessary for meeting the top-level objectives were identified. These lower-level objectives make it easier to specify performance measures and describe site impacts. The lower-level objectives are shown in Figures 3-1 and 4-1 for the postclosure and the preclosure periods, respectively.

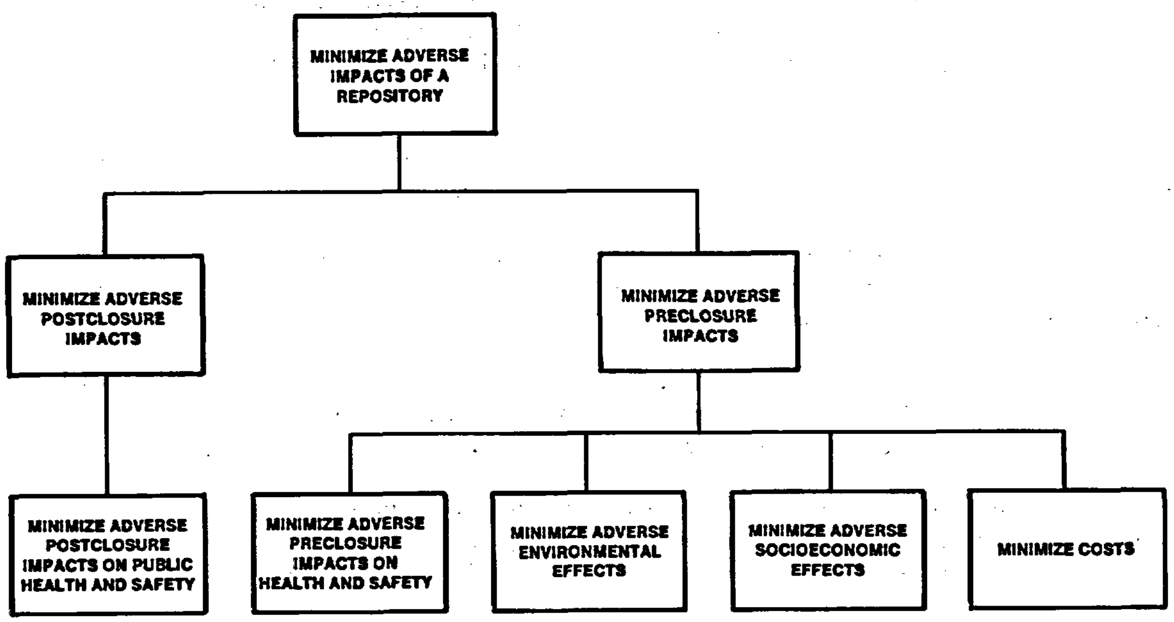

Figure 2-1. General objectives hierarchy for geologic disposal.

Any objectives hierarchy should capture collectively all of the important considerations relevant to a decision. The objectives hierarchy of Figure 2-1 (and Figures 3-1 and 4-1) is assumed to satisfy this goal because the objectives are derived from the DOE's system guidelines and technical guidelines (see Section 2.4), which were developed through an extensive process of consultation, public comment, and NRC concurrence. In developing an objectives hierarchy, care must be taken to avoid double-counting objectives. Extra or unnecessary objectives make the analysis more complex and reduce the quality of the insights provided.

After a hierarchy of objectives is developed, "yardsticks" must be devised to indicate how well a site meets them. Formally, these yardsticks are known as performance measures. The development of performance measures is a process that requires professional judgment, knowledge, and experience. Ideally, performance measures should be expressed in natural scales based on physical measurements or quantitative data. An example is the performance measure of millions of dollars for the objective "minimize costs." Inevitably, however, some measures concern intangible impacts that are not easily described or quantified. For these cases a performance measure must be constructed, as illustrated by the example in Table 2-1. The ranges spanned by any performance measure should be realistic in order to describe the impacts of all sites being evaluated.

In this particular application of the multiattribute utility analysis, a graphic device known as an influence diagram was constructed for each performance measure. The influence diagrams, shown for all performance measures in Appendixes B and E, indicate the factors that must be accounted for in describing the possible site impacts and the interrelationships among these factors. An example of an influence diagram is shown later in the chapter (Figure 2-2). Many of the factors in the influence diagrams may be derived directly from the statements of the disqualifying, favorable, or potentially adverse conditions in the siting guidelines.

Step 2: Specify Scenarios That, if They Occur, Might Affect Postclosure Performance

A good repository site should perform well under nominal, or expected conditions. It should also perform well even if the site contains unexpected features or if disruptive events and processes occur. To estimate and account for risks, it is necessary to identify the disruptions that may adversely affect each site and to estimate the performance of the repository under these conditions.

To account for the risks of unexpected features and disruptive events or processes, scenarios are used in the postclosure analysis of sites. (As explained in Appendix F, preclosure accident scenarios are not considered because they are not expected to be significant site discriminators.) Scenarios are postulated conditions or sequences of processes or events that could affect the postclosure performance of a repository. Each scenario may be regarded as a possible "future" for a repository over a 10,000-year of the period. Examples of scenarios would be exploratory drilling within the controlled area around a repository and movement of a large fault in the repository.

Table 2-1. Example of constructed performance measure for the objective "minimize biological impacts" for a specific problem context*

Score	Description
0	No loss of productive wetland and no members of rare species present
1	Loss of 320 acres of productive wetland and no members of rare species present
2	Loss of 640 acres of productive wetland and no members of rare species present or 30 members of rare species present and no productive wetland loss
3	No loss of productive wetland and 50 members of rare species present
4	Loss of 640 acres of productive wetland and 40 members of rare species present
5	Loss of 640 acres of productive wetland and 50 members of rare species present

*Modified after R. L. Keeney, Siting Energy Facilities, Academic Press, New York, 1980.

For a scenario to be considered for a site, it must satisfy two conditions. First, it must be reasonably likely to occur. Sequences of events or processes that are impossible or so unlikely as to not merit serious attention are not considered. Second, a scenario must have a chance of producing a significant change in repository performance. For example, the score achieved by a site should change from the nominal case by at least one unit if the scenario occurs.

Scenarios for each site were developed by a panel of individuals selected for their expertise in the processes and events that might alter repository performance. Lists of scenarios were screened to find those with some likelihood of occurrence and a potential for affecting performance. Scenarios were designed to be nonoverlapping (so that the occurrence of any one would preclude the occurrence of any other) and exhaustive (so that one and only one scenario could be presumed to occur). The panel provided judgmental estimates of the probability of each scenario's occurring at each site. Since panel members differed slightly in their estimates, high- and low-probability estimates were provided in addition to base-case estimates.

Step 3: Score Each Site on Each Measure and for Each Scenario

The next step in the methodology is to assess each site, using the performance measures developed in step 1 and the scenarios developed in step 2. For the preclosure analysis, such assessments result in a base-case estimate and a range for the possible impacts of each site indicated in terms of the performance measures. These estimates are based on technical models, data, and professional experience. For the postclosure analysis, base-case estimates and a range are provided for the nominal-case scenario and for each of the disruptive scenarios that apply to that site. These estimates are based on technical analyses and professional judgments.

Step 4: Assess the Multiattribute Utility Function

To account for differences in the importance of different impacts, it is necessary to assess values for different impact levels, and these values must be used to arrive at a common scale of desirability. Such a scale is referred to as a "utility scale," and the transformation from impacts to utility is provided by a multiattribute utility function for both preclosure and postclosure performance. For the preclosure analysis, a scale of 0 to 100 was adopted, with 0 assigned to the highest and 100 assigned to the lowest of possible impact levels. For the postclosure analysis, 100 was also assigned to the lowest possible impact level, but the possibility of a negative utility was also included in the scale. On the postclosure scale, a 0 represents just meeting applicable regulatory requirements. The desirability of any site can be indicated by its utility by substituting the impact levels into the multiattribute utility function. Higher utilities imply preferred consequences (i.e., sets of impacts). In cases of uncertainty, the mathematical expected utility, obtained by multiplying the probabilities of consequences by the utilities of these consequences, is the appropriate indicator of site desirability (see von Neumann and Morgenstern, 1947).

The multiattribute utility function assessed for this analysis is presented in Appendix G. As discussed in detail in this appendix, it is constructed from responses to many detailed questions about value judgments appropriate for the site evaluations. Because such value judgments are largely policy, rather than technical, judgments, they were elicited from DOE management.

Step 5: Aggregate Impacts and Values To Provide an Overall Evaluation of Nominated Sites

At this point in the methodology, four sets of information are available: (1) probabilities for each postclosure scenario for each site, (2) a collection of postclosure-impact estimates for each postclosure scenario at each site, (3) a collection of preclosure-impact estimates for each site, and (4) the multiattribute utility function. These sets of information are aggregated into a composite evaluation of sites in three steps.

In the first step, for each site and postclosure scenario, the utility is calculated for each consequence. This is multiplied by the corresponding scenario-probability estimate, and the results are summed to obtain the expected postclosure utilities for each site. These expected utilities indicate the relative postclosure desirability of each site. Sensitivity analyses were used to examine the implications of uncertainties in the postclosure analysis.

In the second step, the utility of each consequence representing preclosure site impacts is determined by using the preclosure utility function. These utilities indicate the relative preclosure desirability of each site. Sensitivity analyses were also used to examine the implications of uncertainties in the preclosure analysis.

The third step is to combine the various expected postclosure and preclosure utilities into an overall composite utility for each site. This is accomplished by multiplying both preclosure and postclosure utilities by weights obtained from assessed value judgments about the relative importance of postclosure and preclosure impacts.

The most difficult of the value judgments concern value tradeoffs, which may involve impacts of a similar nature (e.g., costs of one type versus costs of another type, different types of environmental impacts, and different health-and-safety impacts) or impacts of a different nature (e.g., health effects versus costs). The value tradeoffs among impacts of a similar nature may be easier to make and to clarify and justify than the value tradeoffs between impacts of different types. To specify the value tradeoffs between health effects and costs or between costs and environmental as well as socioeconomic impacts is not an easy task. And yet it may be that these value tradeoffs are crucial to establishing the relative desirability of the nominated sites. Because of this possibility, they should be explicitly considered in the analysis. The value judgments assessed for this purpose are presented in Appendix G.

Step 6: Perform Sensitivity Analyses

The purpose of sensitivity analyses is to test how the overall utilities calculated in step 5 change as assumptions and judgments change. If the implications from the original analysis are resilient under changes in assumptions and judgments, they are more likely to be valid. An obvious sensitivity analysis is to vary the value judgments, since different people have different opinions on the relative importance of various siting impacts. Other input data for the methodology, such as the site impacts (step 3), should also be varied.

Summary

One of the major assets of the decision-aiding methodology is that it divides the problem of selecting sites for characterization into several parts that can be analyzed and scrutinized more easily. The methodology does not reduce the professional judgment required in selecting sites for characterization. By following the sequence of steps outlined above, however, the DOE hopes to make these scientific and policy judgments explicit to the reviewer. The methodology does this in essentially five ways. First, it specifies and organizes the DOE's siting objectives. Second, it provides a means for summarizing how well each site meets each objective. Third, it provides a means for specifying alternative value judgments about the relative importance of impacts with respect to each objective. Fourth, it provides a systematic way to aggregate site impacts on individual objectives. Finally, the methodology allows the DOE to test how implications change as judgments and assumptions change.

2.3 APPLICATION PROCESS AND PARTICIPANTS

Having identified and described the steps in the methodology, it is worthwhile to discuss briefly the process and participants involved in conducting the steps in the methodology. Additional details on the application process are given in Chapters 3 and 4. The participants and their qualifications are listed in Appendix A.

A task force for developing and carrying out the methodology was established within the DOE's Office of Civilian Radioactive Waste Management (OCRWM), and a management plan for this purpose was developed. The task force was composed of three separate groups. One group, consisting of DOE staff and experts in decision analysis and other disciplines, was responsible for seeing that the methodology was carried out according to the procedures and sequence of application recommended in the professional literature. This group was under the general oversight of the senior DOE managers (see below). The other two groups provided the two major inputs required for the methodology: technical judgments and value judgments.

To provide the technical judgments, six panels of technical specialists were established. Each panel was responsible for a major technical area represented in the siting guidelines, and the responsibilities of the panels are consistent with functional responsibilities and staff responsibilities for program execution within the OCRWM. Specifically, panels were established to evaluate all sites in the following areas:

- Postclosure repository performance.
- Preclosure radiological safety.
- Environment.
- Socioeconomics.
- Transportation.
- Ease and cost of siting, construction, operation, and closure.

The technical specialists were thoroughly familiar with the information (i.e., data, models, etc.) contained in all five environmental assessments (DOE, 1986a-e) and with the siting guidelines. They developed the measures for quantifying levels of performance, the scenarios and probabilities required to assess postclosure repository performance, and the estimates of the performance (i.e., scores) of each site on each performance measure. A decision analyst assisted in the process of constructing the performance measures and scenarios and formally elicited the probability of each postclosure scenario for each site. The decision analysts were less involved in the estimation of performance, since this is mainly the purview of the technical specialists.

The technical knowledge and experience of the individuals participating on each panel varied, depending on the responsibilities of the panel (e.g., assessments of postclosure repository performance are highly multidisciplinary, requiring experts in geology, hydrology, geochemistry, performance assessment, nuclear physics, etc.). All technical specialist panels consisted of a lead person from DOE headquarters and technical support staff. None of the three DOE Operations Offices that are involved in the repository program or their prime contractors participated in the scoring of the sites.

The aspects of the methodology that deal with preferences—that is, value judgments—were assigned to DOE management. In particular, four senior DOE managers in the Office of Civilian Radioactive Waste Management participated in the specification of the siting objectives, the verification of independence assumptions required to define the multiattribute utility function, and the specification of utility curves and value tradeoffs among objectives. The decision analysts formally elicited these value judgments. Care was taken to maintain separation between technical and value judgments. Thus, the DOE managers had no knowledge of the formal estimates of site impacts, and the technical specialists had no knowledge of the value tradeoffs among impacts before their aggregation into the composite evaluation of the sites reported here.

2.4 RELATIONSHIP BETWEEN THE ANALYSIS AND THE SITING GUIDELINES

The decision-aiding methodology must be consistent with the DOE siting guidelines, 10 CFR Part 960 (DOE, 1984). This consistency can be explained most easily after briefly reviewing the structure of the guidelines.

The siting guidelines are organized into three categories: implementation (see below), postclosure guidelines, and preclosure guidelines. The postclosure guidelines deal with the siting considerations that are most important for ensuring long-term protection (10,000 years) for the health and safety of the public. The preclosure guidelines deal with the siting considerations important to the operation of a repository before it is closed (about 80 years), such as protecting the public and repository workers from exposures to radiation, protecting the quality of the environment, mitigating adverse socioeconomic impacts, and the ease and cost of repository construction and operation. Both the postclosure and the preclosure guidelines are divided into system and technical guidelines. System guidelines contain broad repository-performance requirements that are largely derived from applicable regulations promulgated by the U.S. Environmental Protection Agency (EPA) and the U.S. Nuclear Regulatory Commission (NRC). The technical guidelines specify requirements on one or more elements of the repository system. Each guideline (system and technical) contains a qualifying condition. Taken together, these qualifying conditions are the minimum conditions for site qualification. Twelve technical guidelines also contain disqualifying conditions, which describe a condition so adverse as to constitute sufficient evidence to conclude, without further consideration, that a site is disqualified. Both the postclosure and the preclosure technical guidelines specify conditions that would be considered favorable or potentially adverse.

As explained in Section 2.2, a basic premise of the decision-aiding methodology is that the overall desirability of a site is related to the extent to which the site achieves the various objectives of site selection. The identification of objectives is a very important task in any siting problem. This task was simplified here because the objectives are readily derived from the siting guidelines, especially from the system guidelines.

At a broad level, the DOE believes that it is important to ensure that the fundamental concerns of the guidelines have been reflected in the methodology. Toward this end Table 2-2 has been prepared as a guidelines-to-objectives index. As can be seen, all guidelines* can be traced to one or more objectives. In fact, some guidelines--for example, the technical guideline on transportation--correspond to more than one objective defined for use in the methodology. Besides the statements of the guidelines themselves, the interested reader is referred to the "Supplementary Information" and Appendix IV of the guidelines (DOE, 1984) for evidence of the correspondence between the guidelines and the objectives.

With regard to the favorable and potentially adverse conditions, these conditions are intended to provide preliminary indications of system performance and are intended to be used in the screening phase of site selection, during the search for potentially acceptable sites. Notwithstanding, these conditions are useful at this stage of the siting process as well. Many of the conditions served to guide the specification of the factors in the influence diagrams shown in Appendixes B and E. The influence diagrams, in turn, were used in the scoring process.

As an illustration of the relationship between favorable and potentially adverse conditions and the decision-aiding methodology consider Figure 2-2, which shows a portion of the influence diagram for the postclosure analysis.

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*No attempt was made to include explicitly the disqualifying conditions of the technical guidelines. As explained in detail in Chapters 2 and 6 of each environmental assessment (DOE, 1986a-e), the evidence does not support a finding that any of the sites is disqualified. In addition, it is often the case that the concerns of the disqualifying conditions are represented in the performance measures defined for use in the methodology. For example, the ground-water travel time, the key factor in the disqualifying condition in the guideline on geohydrology, is included in the postclosure performance measures.

Table 2-2. Index showing correspondence between the qualifying conditions of the siting guidelines and siting objectives

Section 960	Guideline	Related siting objective(s)[a]
4-1(a)	System guideline on postclosure performance	Radiological safety of the public for 0 to 10,000 and 10,000 to 100,000 years after closure
4-2-1(a)	Geohydrology	
4-2-2(a)	Geochemistry	
4-2-3(a)	Rock characteristics	
4-2-4(a)	Climatic changes	
4-2-5(a)	Erosion	
4-2-6(a)	Dissolution	
4-2-(a)	Tectonics	
4-2-8-1(a)	Natural resources	
4-2-8-2(a)	Site ownership and control	
5-1-(a)(1)	System guideline on pre-closure radiological safety	Radiological safety, public, repository; radiological safety, workers, repository; radiological safety, public, transportation; radiological safety, workers, transportation
5-1(a)(2)	System guideline on environment, socioeconomics, and transportation	Nonradiological safety, public, repository; nonradiological safety, public, transportation; aesthetic effects; biological effects; archaeological, cultural, and historical effects
5-1(a)(3)	System guideline on ease and cost of siting, construction, operation, and closure	Nonradiological safety, workers, repository; nonradiological safety, workers, transportation; total repository costs; total transportation costs
5-2-1(a)	Population density and distribution	Radiological safety, public, repository
5-2-2(a)	Site ownership and control	Radiological safety, public, repository
5-2-3(a)	Meteorology	Radiological safety, public, repository; nonradiological safety, workers, repository; total transportation costs
5-2-4(a)	Offsite installations and operations	Radiological safety, public, repository; radiological safety, workers, repository; total repository costs
5-2-5(a)	Environmental quality	Nonradiological safety, public, repository; aesthetic effects; biological effects; archaeological, cultural, and historical effects
5-2-6(a)	Socioeconomic impacts	Socioeconomic effects

Table 2-2. Index showing correspondence between the qualifying conditions of the siting guidelines and siting objectives (continued)

Section 960	Guideline	Related siting objective(s)[a]
5-2-7(a)	Transportation	Radiological safety, public, transportation; radiological safety, workers, transportation; nonradiological safety, public, transportation; nonradiological safety, workers, transportation; total transportation costs
5-2-8(a)	Surface characteristics	Nonradiological safety, workers, repository; total repository costs
5-2-9(a)	Rock characteristics	Nonradiological safety, workers, repository; total repository costs; radiological safety, public, repository; radiological safety, workers, repository
5-2-10(a)	Hydrology	Nonradiological safety, workers, repository; total repository costs
5-2-11(a)	Tectonics	Nonradiological safety, workers, repository; total repository costs

[a]The objectives listed here are abbreviated versions of the objectives. The full statements of the objectives are given in Tables 3-1 and 4-1 for the postclosure and the preclosure periods, respectively.

The top half of the diagram contains a number of double ellipses, which indicate the most significant factors in the diagram. These factors can be readily associated with a number of favorable and (or) potentially adverse conditions specified for the technical guidelines on geohydrology, geochemistry, and rock characteristics. For example, the ground-water travel time (ellipse (26)) is a factor in favorable condition 1 and the criterion for the disqualifying condition for the guideline on geohydrology. (Ground-water travel times can be calculated from knowledge of the more-specific site conditions listed in favorable condition 4 as well.) Ground-water flux (ellipse (28)) is mentioned in potentially adverse condition 1 of the geohydrology guideline and favorable condition 4 of the geochemistry guideline. Retardation (ellipse (27)) is a factor listed in favorable conditions 2 and 5 and potentially adverse condition 2 of the geochemistry guideline. Tens and probably hundreds of other examples of direct ties to favorable or potentially adverse conditions could similarly be shown if all the influence diagrams were so broken down.

Many of the ties between factors in the influence diagrams with the guideline conditions are more subtle and complex than the preceding paragraph would indicate. For example, again referring to Figure 2-2, waste-package lifetime (ellipse (35)) has ties to favorable conditions 2, 4, and 5 and potentially adverse conditions 1 and 3 of the geochemistry guideline as well as potentially adverse conditions 2 and 3 of the rock-characteristics guideline. Many more examples of these interrelationships could be derived on comparisons of the guideline conditions and the influence diagrams.

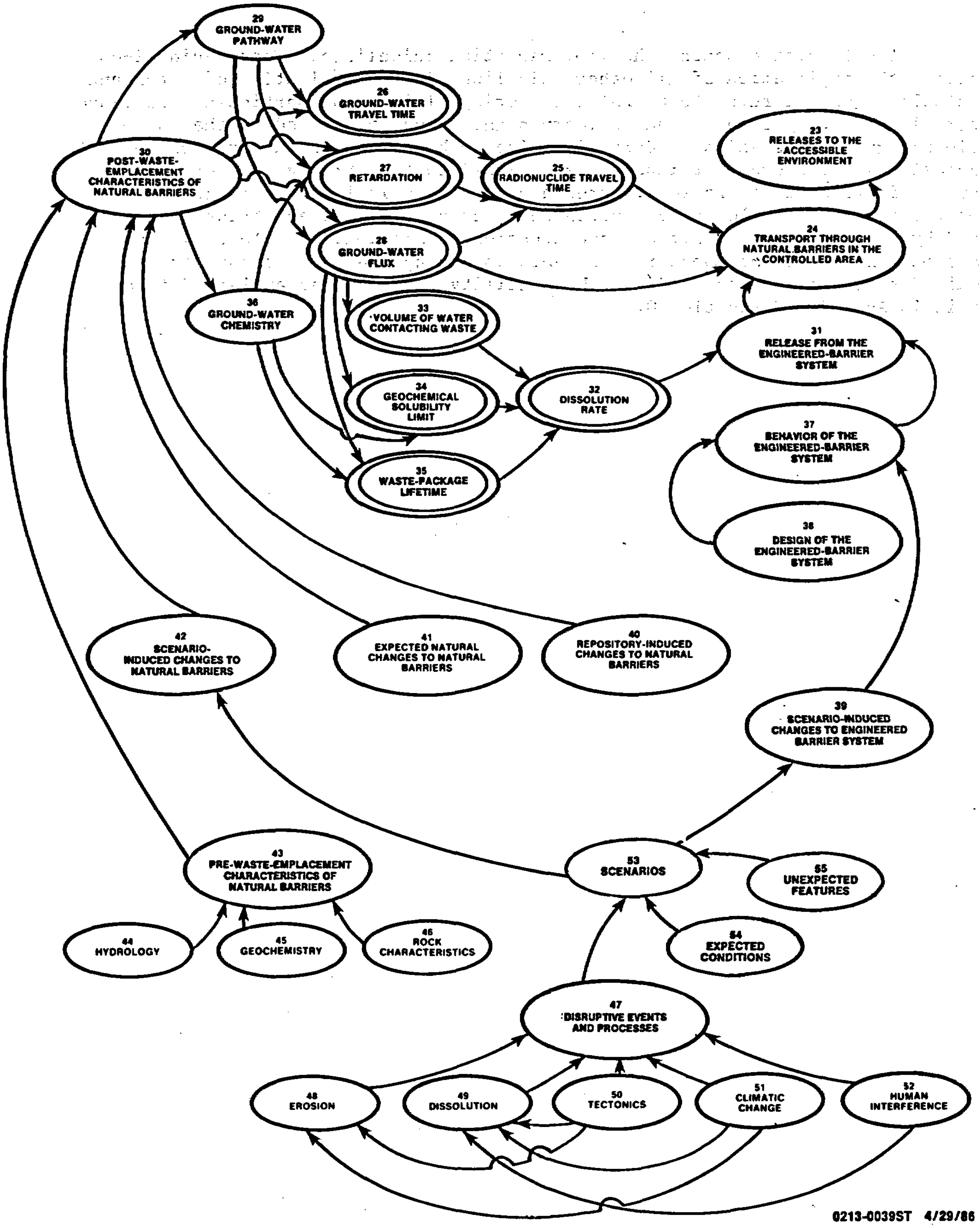

Figure 2-2. Partial diagram showing relationships among factors influencing the numbers of postclosure health effects attributable to the repository. (See Figure 3-2 for complete diagram.)

A final point concerns the implementation guidelines. These guidelines govern the application of all other guidelines in the evaluation of sites and establish general rules to be followed during siting. Of particular relevance here is that they require that primary significance be placed on the postclosure guidelines and secondary significance be placed on the preclosure guidelines. The order of importance assigned to the three groups of preclosure guidelines is as follows: preclosure radiological safety is given the most importance, followed by environment, socioeconomics, and transportation and by ease and cost of siting, construction, operation, and closure. The DOE has met the intent of these requirements in making the value tradeoffs required to establish the multiattribute utility function, as explained in detail in Appendix G (Section G.5).

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Chapter 3

POSTCLOSURE ANALYSIS OF THE NOMINATED SITES

As described in Chapter 2, the formal decision-analysis method known as multiattribute utility analysis was applied to obtain a quantitative comparison of the five sites nominated as suitable for characterization. The application independently evaluated the estimated performance of a repository at each potential site before and after closure. This chapter describes the analysis of postclosure performance.

The components of the postclosure analysis are presented in the various sections of this chapter. Section 3.1 describes the objectives selected to guide the analysis. Section 3.2 summarizes the performance measures defined to quantify the degree to which these objectives are achieved. Section 3.3 discusses the scenarios, or sequences of processes and events, that could affect the postclosure performance of a repository and the judgmental probabilities assigned for each scenario at each site. Section 3.4 describes the performance estimated for each site, expressed in terms of performance measures, for each applicable scenario. Section 3.5 describes the multiattribute utility function developed to integrate the various assessments into an overall postclosure evaluation and the various value judgments for the analysis. Numerical results and sensitivity analyses are presented in Section 3.6. Finally, the conclusions derived from the postclosure analysis are summarized in Section 3.7.

3.1 THE OBJECTIVES HIERARCHY

As noted in Chapter 2, a multiattribute utility analysis is based on the premise that the relative desirability of a site is determined by the extent to which the selection of that site would achieve the siting objectives. The implementation of this logic requires that site-selection objectives be made explicit. For this reason, specific statements of performance objectives for the long-term period after repository closure were developed. Postclosure objectives establish the basis for judging the suitability of a site after repository closure and guide the specification of quantitative performance measures.

Objectives may be stated as very broad and general goals, such as minimizing adverse impacts on the health and safety of the public after closure, or as specific objectives that must be achieved in order for the general objectives to be achieved, such as minimizing the number of health effects attributable to radionuclide releases from a repository. For the application of a multiattribute utility analysis, specific and relatively detailed objectives are required.

Objectives for the postclosure analysis were established by proposing alternative sets of postclosure objectives and then evaluating these alternatives. The basis for generating alternative sets of postclosure objectives was provided by the general siting guidelines published by the U.S.

Department of Energy (DOE) as 10 CFR Part 960 (DOE, 1984). The selection among these alternatives was based on consistency with the intent and history of the siting process as well as on criteria of completeness, nonredundancy, significance, operationality, and decomposability.

The fundamental criterion for judging the postclosure performance of a repository* was assumed to be the extent to which the repository would minimize, after closure, the adverse impacts on public health and safety that could result from exposure to the radionuclides in the waste. This view is consistent with the Nuclear Waste Policy Act of 1982 (the Act), the DOE siting guidelines, and regulations established by other agencies. The length of this postclosure period has been established by the U.S. Environmental Protection Agency in 40 CFR Part 191, Subpart B (EPA, 1985), to be 10,000 years after closure. In evaluating the postclosure performance of a repository, it is necessary to consider not only performance under the conditions expected for the first 10,000 years after closure, but also the effects of potentially disruptive natural phenomena and inadvertent human interference. In addition, the implementation provisions of the siting guidelines (10 CFR 960.3-1-5) call for comparisons of the undisturbed performance of alternative sites for 100,000 years to support the recommendation of sites for the development of repositories. The DOE believes that sites capable of meeting the stringent requirements for these time periods would continue to provide safe isolation for even longer time periods.

Accordingly, two objectives were defined:

1. Minimize the adverse health effects attributable to the repository during the first 10,000 years after closure.

2. Minimize the adverse health effects attributable to the repository during the period 10,000 to 100,000 years after closure.

The term "minimize" is used in the statements of the above objectives to indicate that, all other things being equal, a repository system that leads to the fewest postclosure health effects would be preferred. It must be recognized that preclosure considerations (such as the desire to avoid significant environmental impacts and economic costs) may make strict minimization (i.e., selecting the site that would produce the smallest number of postclosure health effects regardless of costs or other preclosure considerations) undesirable. Performance against the above objectives may have to be traded off to obtain improved performance against preclosure objectives. Making any necessary tradeoffs of one objective against another in a way that is consistent with the fundamental values of our society is one of the principal goals of multiattribute utility analysis.

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*In this chapter, terms like "repository performance" mean the performance of the total repository system--that is, the geologic setting at the site and the engineered barriers, all acting together to contain and isolate the radioactive waste.

Defining objectives in terms of health effects ensures that proper consideration will be given to the various means by which sites might minimize adverse health effects. Alternative site-selection objectives, such as "maximize the physical separation of radioactive waste from the accessible environment after closure" or "maximize the flexibility to use engineered barriers to ensure compliance with applicable regulations" derive their importance from being means to minimize health effects. Basing objectives on end consequences ensures that criteria defined in terms of the means for achieving the desired consequences will be taken into account and assigned an appropriate degree of importance.

The two postclosure objectives defined above could be combined into a single objective of minimizing health effects for 100,000 years after repository closure. Alternatively, these objectives could be further split into subobjectives that cover shorter time intervals, such as minimizing health effects from 0 to 1000 years, from 1000 to 10,000 years, from 10,000 to 25,000 years, and so forth. Because there is little evidence that health effects would occur at appreciably different times for different repository sites, only two time periods were considered.

Figure 3-1 shows the two postclosure objectives displayed as part of a simple objectives hierarchy. The hierarchy indicates that the two lower-level objectives must be achieved in order to achieve the higher-level objective of minimizing adverse impacts on public health and safety after closure.

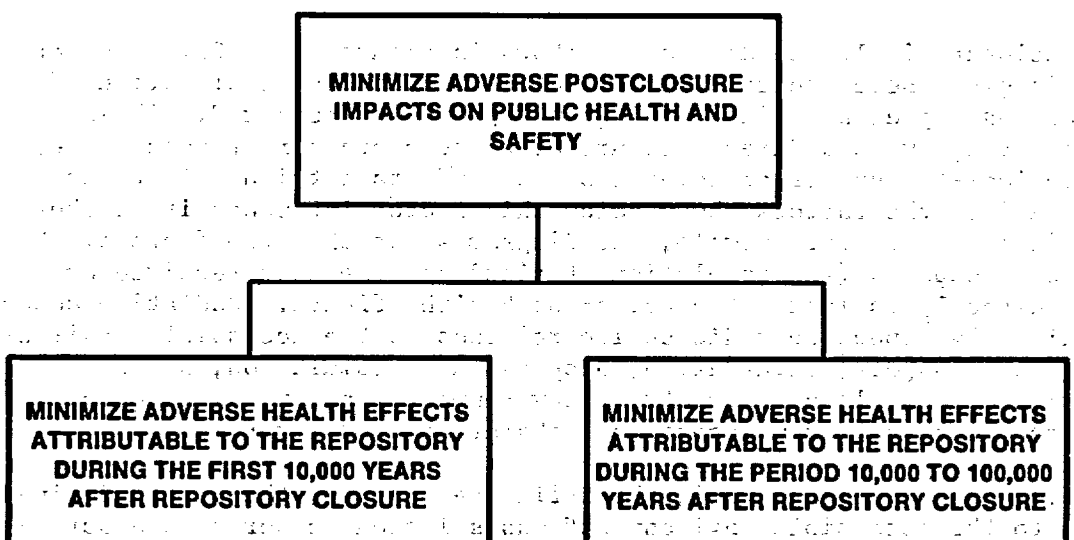

Figure 3-1. Postclosure objectives hierarchy.

3.2 PERFORMANCE MEASURES

The second step in the postclosure analysis consisted of defining performance measures to quantify the degree to which a site achieves each postclosure objective. According to the multiattribute utility theory, performance measures can be either direct or indirect (surrogate) measures of objectives. For example, the following would be a direct measure for the objective of minimizing the health effects attributable to the repository: the total number of premature deaths from cancer that are attributable to the repository. However, it is sometimes difficult or impractical to use direct performance measures. In this analysis, the use of direct measures, such as the example given above, was judged impractical because the size and the geographic distributions of populations, dietary habits, and ways of life will undoubtedly change over a period of 10,000 years. These factors, which must be known to estimate health effects, cannot be usefully predicted over such long periods of time. For this reason, appropriate surrogates were sought to serve as more useful measures of performance.

3.2.1 METHODS USED IN THE DEVELOPMENT OF PERFORMANCE MEASURES

The first step in the development of performance measures for the postclosure analysis was the identification of the key factors that affect the number of postclosure health effects that might result from a repository at a given site. To help summarize these factors and to illustrate the relationships among them, a diagram was constructed. Called an "influence diagram," this diagram shows the major cause-and-effect and other influencing relationships among the identified factors.

The postclosure influence diagram is shown in Figure 3-2. Only a brief explanation is given here because a detailed description and explanation of the relationships represented in the diagram appear in Appendix C. Shown at the top of the diagram is a direct measure of postclosure performance in any given time period—the number of adverse health effects attributable to the repository. All of the factors shown below this factor influence it, either directly or indirectly. For example, the diagram shows that two factors, the number of people exposed (the population at risk) and the dose received by each person, directly influence the number of health effects. Radiation doses, in turn, indirectly depend on radionuclide releases to the accessible environment and on the transport, retardation, dispersion, accumulation, and uptake of those radionuclides along a variety of environmental pathways. The doses received by people result from ingestion, inhalation, and immersion.

Of the various factors shown in the influence diagram, the factor defined as "releases to the accessible environment" was selected to serve as a surrogate for health effects. There were two reasons for this choice. The first reason is practicality. Even though the diagram shows a number of factors whose influence on health effects is more direct than that of releases (examples are radiation doses received through ingestion, inhalation, and immersion), these factors cannot be estimated for the next 10,000 to 100,000 years. As mentioned, it is not possible to predict the long-term changes in the environment, population distributions, and behavioral patterns that determine how releases result in the doses received by people. Although there may

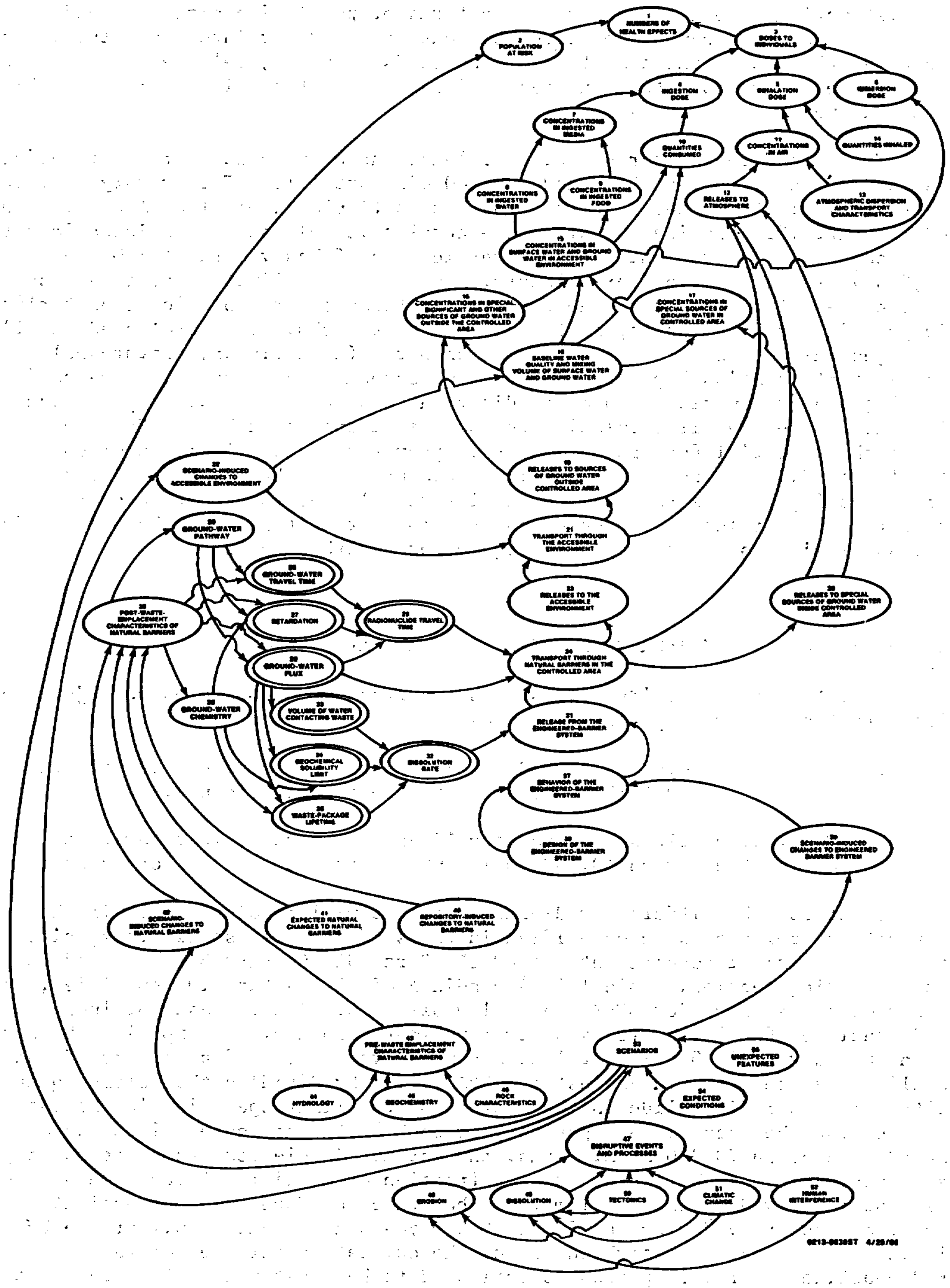

Figure 3-2. Relationships among the factors influencing the numbers of postclosure health effects attributable to the repository.

be distinctions among the sites now in terms of population size and land use, these distinctions cannot be reasonably extrapolated far into the future. An argument that, over the next tens of thousands of years, releases at one site will be less hazardous than the same releases at another site would be highly speculative.

The second reason for selecting releases as a surrogate for health effects is consistency with the EPA standards (40 CFR Part 191). The primary containment requirements of the EPA standards, in particular Table 1 of Appendix A of 40 CFR Part 191, specify the allowable cumulative releases of radionuclides to the accessible environment per 1000 metric tons of heavy metal (MTHM) for 10,000 years after repository closure. These release limits were established by the EPA after evaluating the expected performance of geologic repositories in generic basalt, granite, salt, and tuff host rocks. They are based on (1) very general models of environmental transport; (2) a linear, nonthreshold dose-effect relationship between radiation exposures and premature deaths from cancer; and (3) current population distributions and death rates. For each 1000 MTHM, the overall cumulative-release limit specified by the EPA represents the potential for approximately 10 premature deaths from cancer during the first 10,000 years after repository closure. The EPA has, in effect, provided scaling factors that relate cumulative releases to premature deaths from cancer. Thus, releases expressed as fractions or multiples of the overall EPA release limit provide a useful surrogate for health effects.

3.2.2 PERFORMANCE MEASURES SELECTED FOR THE ANALYSIS

Selecting radionuclide releases as a surrogate for postclosure objectives leads to the following performance measures:

1. Cumulative releases of radionuclides to the accessible environment during the first 10,000 years after repository closure.

2. Cumulative releases of radionuclides to the accessible environment during the period 10,000 to 100,000 years after repository closure.

To account for the different radionuclides that will be disposed of in the repository, releases were quantified in terms of the release limits specified by the containment requirements of 40 CFR Part 191, Subpart B. As noted in the preceding section, Table 1 in Appendix A of 40 CFR Part 191 specifies, in terms of curies per 1000 MTHM, the allowable cumulative releases of individual radionuclides for 10,000 years after repository closure. As explained by Note 6 in Appendix A of 40 CFR Part 191, a cumulative release of a mixture of radionuclides can be compared against the EPA limits by dividing the release quantity for each radionuclide in the mixture by the limit specified in the table and summing the result. A repository at each of the nominated sites was assumed to contain 70,000 MTHM. Thus, the estimated releases from a repository at a given site can be expressed as a fraction or multiple of the same weighted total allowed by the EPA limits. The statement "the releases estimated for the repository during the first 10,000 years are equal to 0.1 of the EPA limits" means that the weighted sum of the cumulative releases of various radionuclides over this period is estimated to be one-tenth of the EPA limit. The EPA limits were also used as a basis to establish a scale for measuring cumulative releases during the period 10,000 to 100,000 years after closure. Thus, the statement "cumulative releases of radionuclides for 10,000 to 100,000 years after repository closure are estimated to be 0.1 of the EPA limits" means that the cumulative releases over this 90,000-year period are estimated to be one-tenth of the EPA limits for the first 10,000 years.

Table 3-1 summarizes the correspondence between postclosure objectives and performance measures and the units in which performance is expressed. As noted in the table, y_1 is used to designate the performance measure for the first 10,000 years and y_2 the performance measure for the second time period, 10,000 to 100,000 years.

Table 3-1. Objectives and performance measures for the postclosure period

Objective		Performance measure	Units
1. Minimize the total number of health effects attributable to the repository during the first 10,000 years after 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 Table 1 and Note 6 of Appendix A of 40 CFR Part 191 for the first 10,000 years
2. Minimize the total number of health effects attributable to the repository during the period 10,000 to 100,000 years after closure	y_2:	Cumulative releases of radionuclides to the accessible environment during the period 10,000 to 100,000 years after repository closure	Multiples of the release limits specified by Table 1 and Note 6 of Appendix A of 40 CFR Part 191 for the first 10,000 years

3.3 SCENARIOS

The releases that will occur if the repository is located at a particular site obviously depend on the processes and events that will occur at that site, such as major earthquakes. The influence of such processes and events on releases, and therefore health effects, is represented in the influence diagram (Figure 3-2) by the ellipse labeled "scenarios." The scoring of each site in terms of releases was based on specific scenarios. Credible scenarios were developed by identifying the different processes, events, and conditions that might affect the performance of a repository at a site.

3.3.1 METHOD USED FOR IDENTIFYING SCENARIOS

The set of scenarios used in estimating releases was developed through a sequence of steps conducted by a panel of technical specialists under the general guidance of the methodology lead group. The various participants are identified in Tables A-1 and A-2 of Appendix A. First, the various conditions that could affect postclosure performance were identified. As shown in the influence diagram of Figure 3-2, disruptive scenarios can affect health effects by (1) altering the characteristics of the engineered barriers so as to change the rate and the magnitude of the release of radionuclides; (2) altering the characteristics of the natural barriers so as to change the rate of radionuclide transport to the accessible environment; (3) altering the accessible environment in ways that affect the extent to which the released radionuclides change the concentration of radionuclides in sources of ground water; and (4) altering the population at risk. Because the last two mechanisms do not affect releases, the development of scenarios focused on the mechanisms that affect releases from the engineered-barrier system and transport through the natural barriers in the controlled area.

As shown in Figure 3-2, the releases from a repository are affected by such factors as the ground-water travel time, flux, and chemistry as well as the rates of radionuclide dissolution and retardation. Conditions relating to or altering these factors thus potentially affect releases. Three categories of conditions were considered: (1) expected conditions (nominal case), (2) unexpected features, such as undetected faults, and (3) disruptive processes and events. Many studies in the past several decades have attempted to identify and evaluate processes and events that may affect the performance of a repository. This literature was reviewed to aid the identification of relevant conditions. In accordance with 40 CFR Part 191, Subpart B, only the disruptive processes and events that might occur in the first 10,000 years after closure were considered. In all cases, however, the effects of postulated conditions were evaluated for both the first 10,000 years and the period 10,000 to 100,000 years.

To identify scenarios that pose a credible risk to the performance of a repository, the individual and combinations of conditions falling into the above categories were screened by applying two criteria. First, any process or event judged to be incapable of increasing releases by more than 10 percent from those for expected conditions, regardless of the other conditions that might occur, was excluded, unless the process or event was also judged to have a high probability (more than 1 chance in 10) of occurrence. Second, a process or event judged to have a probability of less than 1 chance in 10,000 over 10,000 years was eliminated unless it was judged possible that the occurrence of the scenario might increase releases by a very great amount (so that the product of the probability and the factor by which releases might be increased would be greater than 0.01). When there was reasonable doubt as to whether a process or event should be eliminated, it was retained.

The final step in the process was to construct sequences of the remaining events and processes that might lead to impacts on repository performance. Table 3-2 lists the scenarios that were developed. The scenarios were judged to encompass all of the significant phenomena, processes, or events that might occur at the sites. The scenarios are mutually exclusive because it was assumed that the occurrence of a scenario implied the occurrence of only the events specified by the scenario (and none of the events specified by other scenarios). Although scenarios involving combinations of the conditions indicated in the table were considered, such scenarios were eliminated in the screening. A detailed explanation of the scenarios and their development can be found in Appendix C.

Table 3-2. Potentially significant scenarios

Scenario	Description
1	Nominal case (expected conditions)
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

3.3.2 ASSIGNMENT OF PROBABILITIES TO SCENARIOS

Each scenario was assigned probabilities that indicate the judged likelihood of occurrence at each site. These probabilities were assessed by a panel of technical specialists selected for their expertise in the processes and events that could affect the performance of the repository. The members of the panel are listed in Table A-2 of Appendix A.

Care must be taken in generating judgmental probabilities if the probabilities are to reflect accurately the underlying knowledge and beliefs of the persons who generate them. To help avoid errors in assessed probabilities, panel members were introduced to the theory of judgmental probability and apprised of the biases that experiments (e.g., Kahneman, Slovic, and Tversky, 1982) have shown can produce distortions in probability estimates. Panel members practiced making probability estimates by using a broad range of sample questions. The probabilities estimated by each panel member were then tabulated and compared with the actual answers to the sample questions. This permitted each panel member to test his or her skill at assessing judgmental probabilities and provided an increased awareness of the need to avoid potential biases that might affect the assessments.

The process by which the panel made judgmental probability estimates consisted of several steps. At the outset, the panel members reviewed the available information on the scenarios and the estimates of their probabilities. Then, using his or her professional judgment, each panel member individually provided initial best-judgment, high, and low estimates of the probability of occurrence of a given scenario at a particular site. The high probability was that person's recommended upper bound for the probability. Similarly, the low-probability estimate was the panel member's recommended lower bound for the probability. After the various probability estimates were tabulated, summary statistics were computed and presented to the panel. The results were then discussed by the panel members, including the merits of higher versus lower estimates. After the discussion, some members elected to modify some of their initial estimates. Finally, by consensus, the panel recommended a set of probabilities to be used in the analysis. Often times, the geometric mean of the suite of individual assessments was selected for the recommended base-case probability, and the highest of the individual high-probability estimates and the lowest of the individual low-probability estimates were selected for the high and the low probabilities.

Table 3-3 shows the judgmental probabilities recommended by the panel for the various site-specific scenarios. Probabilities were not assessed 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 less than one chance in 10,000 over 10,000 years. The decision not to assess probabilities in such cases represented a more rigorous application of the screening criteria that had been applied earlier. Where probabilities were assessed, three probability values--high, base-case, and low--were estimated. All such probabilities were assigned as direct judgments, with the exception of the probability for the nominal case (scenario 1). The probability of this scenario was calculated for each site by summing the probabilities of all the other scenarios and subtracting the result from unity.

As can be seen from Table 3-3, scenario 1 (the nominal case) was viewed as the most likely scenario at all sites (between 96 and 98 percent of the probability in the base case). Scenario 2 (unexpected features) was judged to be the next most likely scenario to occur at all sites, with 1.3 to 2.4 percent of the probability of the base case. Of the disruptive scenarios, exploratory drilling was regarded to be more 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. Movement on a large fault of sufficient magnitude to affect expected repository performance was judged most likely at the Hanford site. A magmatic event of sufficient magnitude to affect expected repository performance was judged most likely at the Yucca Mountain site.

3.4 SITE SCORING

Scoring a site against the postclosure performance measures requires estimating the cumulative releases that would occur from a repository at that site under each of the applicable scenarios. Estimating cumulative releases in the two postclosure time periods is extremely difficult because of limited data and the limited understanding of the mechanisms by which releases can occur. Various performance-assessment models have been developed to estimate releases from the repository over time. Although the results produced by these models are regarded as providing useful bounds, the models are known to be simplifications of the complex processes that are involved.

A more appropriate approach is to augment the results of analyses based on release models with assessments of the accuracies and limitations of the models. This can be accomplished by obtaining direct judgmental assessments

Table 3-3. High, base-case, and low probabilities assessed for scenarios[a]

Scenario[b]	Davis Canyon	Deaf Smith	Richton Dome	Hanford	Yucca Mountain
1[c]	1 9.8×10^{-1} 8.0×10^{-1}	1 9.8×10^{-1} 8.0×10^{-1}	1 9.8×10^{-1} 8.0×10^{-1}	1 9.6×10^{-1} 6.4×10^{-1}	1 9.8×10^{-1} 8.0×10^{-1}
2	1.0×10^{-1} 1.4×10^{-2} 0	1.0×10^{-1} 1.6×10^{-2} 0	1.0×10^{-1} 1.3×10^{-2} 0	2.5×10^{-1} 2.4×10^{-2} 0	2.0×10^{-1} 1.9×10^{-2} 0
3	NC	NC	NC	NC	NC
4	NC	NC	NC	NC	NC
5	NC	NC	NC	1.0×10^{-2} 3.2×10^{-3} 1.0×10^{-5}	NA
6	NC	NC	NC	3.2×10^{-4} 3.2×10^{-4} 3.0×10^{-5}	NA
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} 2.0×10^{-3} 1.0×10^{-5}	1.0×10^{-1} 2.0×10^{-3} 1.0×10^{-5}	1.0×10^{-1} 2.0×10^{-3} 1.0×10^{-5}	NC	NC
13	NA	NA	NA	NA	NA
14	1.0×10^{-3} 1.0×10^{-4} 1.0×10^{-5}	2.0×10^{-3} 2.0×10^{-4} 2.0×10^{-5}	5.0×10^{-3} 5.0×10^{-4} 5.0×10^{-5}	1.0×10^{-1} 1.0×10^{-2} 1.0×10^{-3}	NA

[a]Key: NA = scenario judged to have an insignificant effect on releases; NC = scenario judged to be not credible.

[b] See Table 3-2 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.

of releases from experts who understand the analyses, know the extent and limitations of the data for the sites, and appreciate the complexity of the processes by which releases can occur at a given site.

3.4.1 METHOD OF OBTAINING ASSESSMENTS OF RELEASES

Judgmental assessments of releases were obtained in a two-step process. The first step was to clarify the relationship between releases and the basic hydrologic, geochemical, and geomechanical characteristics of a site. This step was performed by members of the methodology lead group and technical specialists from the postclosure analysis group. The technical specialists were familiar with the processes by which radionuclides could be released from a repository, the available conceptual models for predicting radionuclide release and transport, and the results of analyses conducted with these models. They were also familiar with the level of conservatism in the assumptions incorporated into the release models (when information to support more-realistic assumptions is lacking) and the processes that have been omitted from the models; an example of the latter is the effect of waste-generated heat on the host rock and surrounding units in the repository. The purpose of this step was to state explicitly the best current scientific judgment about the relationship between site characteristics and radionuclide releases for the benefit of those less familiar with the subject.

To make these judgments explicit, descriptions of six hypothetical sites were developed. These hypothetical sites ranged from a site with relatively poor characteristics to one with extremely good characteristics for waste isolation. Consensus estimates of the releases that would occur during each time period from a repository at each of the hypothetical sites were then provided by persons with the most expertise in the assessment of releases. The hypothetical site descriptions were then modified and generalized until an orderly correspondence between releases and site descriptions was obtained.

Figures 3-3 and 3-4 show the relationships between site characteristics and estimated releases. Each figure shows a scale of 0 to 10, with the left-hand side defined in terms of releases expressed as multiples of the EPA release limits and the right-hand side defined in terms of site characteristics. It must be emphasized that various combinations of site characteristics can lead to the same magnitude of releases; that is, the descriptions on the right of the scale are not unique (see Appendix B).

During the first 10,000 years after repository closure, as shown on the left of the scale in Figure 3-3, the releases estimated for the hypothetical sites ranged from a value 10,000 times lower than the EPA release limits to 10 times higher than the EPA limits. This range was judged to encompass all levels of releases that could occur at any of the nominated sites. For the period 10,000 to 100,000 years after closure, release estimates ranged from a value 1000 times lower than the EPA limits to 100 times higher than the limits, as shown in Figure 3-4. This range was similarly judged to encompass all levels of releases that could occur at any of the nominated sites during that time period. A 0 to 10 scale was used to simplify the association of site characteristics with releases.

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	Scale	Characteristics of the Site for Which the Cumulative Releases on the Left Are Judged To Be Reasonable
0.0001	10* 9	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	8 7	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	6 5	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	4 3	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	2 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	0	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. Equivalent combinations of performance factors are given in Table B-1.

Figure 3-3. Scale used to aid the judgmental estimation of releases during the first 10,000 years after repository closure.

PERFORMANCE MEASURE—Cumulative Releases of Radionuclides to the Accessible Environment During the Time Period 10,000 to 100,000 Years After Repository Closure

Cumulative Releases Over the First 10,000 Years as Multiples of the EPA Release Limits	Scale	Characteristics of the Site for Which the Cumulative Releases on the Left Are Judged To Be Reasonable
0.001	10 9	The characteristics and conditions at the site are such that, during the period 10,000 to 100,000 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 90,000 years is about 10 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 300,000 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	8 7	The characteristics and conditions at the site are such that, during the period 10,000 to 100,000 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 90,000 years is about 30 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 250,000 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.
0.1	6 5	The characteristics and conditions at the site are such that, during the period 10,000 to 100,000 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 90,000 years is about 100 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 200,000 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.
1	4 3	The characteristics and conditions at the site are such that, during the period 10,000 to 100,000 years after closure, radionuclide releases to the accessible environment are small. This judgment is based on a combination of site characteristics that implies some 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 90,000 years is about 300 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 150,000 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.
10	2 1	The characteristics and conditions at the site are such that, during the period 10,000 to 100,000 years after closure, radionuclide releases to the accessible environment are significant. This judgment is based on a combination of site characteristics that implies a 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 90,000 years is about 1000 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 about 100,000 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.
100	0	The characteristics and conditions at the site are such that, during the period 10,000 to 100,000 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 90,000 years is about 10,000 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 about 10,000 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. Equivalent combinations of performance factors are given in Table B-2.

Figure 3-4. Scale used to aid the judgmental estimation of releases occurring during the period 10,000 to 100,000 years after repository closure.

The scale was chosen to be geometric (e.g., 0 corresponding to 10 times the release limits, 2 corresponding to the release limits, 4 corresponding to one-tenth the release limit, etc.) to provide greater resolution at low release levels. In view of the performance assessments presented in Section 6.4.2 of the environmental assessments for the nominated sites (DOE, 1986a-e), it was expected that the estimated releases from the sites would be too low for a linear scale to provide sufficient discrimination among sites.

The right-hand sides of the scales shown in Figures 3-3 and 3-4 contain qualitative statements about the factors (shown in Figure 3-2) that affect releases, such as the time of ground-water travel, the ground-water flux, the solubility of key radionuclides, and retardation factors for key radionuclides. As mentioned, there are many combinations of these factors that would lead to the same releases. For example, a site with a long ground-water-travel time and a moderate solubility of key radionuclides may produce the same releases to the accessible environment as one with a moderate ground-water-travel time and a very low solubility of key radionuclides. To account for all of the combinations that are possible, two performance factors were used to summarize the effect of site characteristics on releases:

- A factor, denoted F, for release from the engineered-barrier system; it measures the amount of radionuclides that can be dissolved into the ground water during the period of interest.

- A factor, denoted T_1, for transport through the natural barriers; it measures the time of radionuclide travel from the engineered-barrier system through the natural barriers to the accessible environment under post-waste-emplacement conditions.

These parameters are explained in detail in Appendix B.

3.4.2 PERFORMANCE-MEASURE SCORES

The application of the scales shown in Figures 3-3 and 3-4 to estimate releases was made in a series of workshops attended by the full panel of postclosure technical specialists (see Appendix A). This panel consisted of specialists who were involved in the development of the scales as well as specialists selected for their detailed knowledge of the comparative characteristics of the nominated sites. The sequence of steps conducted at these workshops is summarized below.

For each applicable scenario, beginning with the nominal case, panel members individually provided (by secret ballot) high, best-judgment, and low scores for each site, using the 0 to 10 scales shown in Figures 3-3 and 3-4. Before making these estimates, the panel discussed the relevant characteristics of each site and their significance for releases, using the influence diagram (Figure 3-2) as a guide. The panel then estimated the values of the factors F and T_1 (defined above) for the specified scenario. To obtain an initial best-judgment score for a site for a particular scenario, each member compared the site against the various descriptions shown on the right-hand sides of the scales. The computed estimates of F and T_1 were considered in relation to these descriptions and the equivalent combinations of factors specified in

Tables B-1 and B-2 of Appendix B, taking into account the range of uncertainty in these parameters. If for a given scenario the site was judged to have characteristics comparable to one of the descriptions, it was assigned the even-number score corresponding to that description; if judged to have characteristics that placed it between two of the descriptions, it was assigned the odd-number score between the even numbers corresponding to those descriptions. The high scores of each panel member were to represent site characteristics and releases so favorable that the scorer believed there was only 1 chance in 20 that the actual conditions at the site would be even more favorable. Similarly, the low scores were intended to represent site characteristics and releases so unfavorable that the scorer believed there was only 1 chance in 20 that the actual conditions would be even less favorable.

To reach a decision on a single set of high, base-case, and low scores for a given scenario at a particular site, the panel used a process similar to that used in generating scenario probabilities. The estimates of each panel member were tabulated by representatives of the methodology lead group and reviewed by the panel, with various members presenting arguments for higher or lower estimates. The discussion continued until all members of the panel agreed on a recommended high, base-case, and low score for the scenario. Panel members were then asked to rethink their assessments and to review the data for the site in preparation for a repetition of the scoring exercise two weeks later. The final scores obtained in this second exercise, which differed only slightly from the initial results, are summarized in Table 3-4.

The very low releases implied by the relatively high scores shown in the table should not be surprising. Various preliminary assessments conducted over the last decade have supported the view that, because of the characteristics of the potential host rocks, a loss of waste isolation is highly unlikely. These studies, which used various approaches to analyze the postclosure performance of a repository (e.g., qualitative comparisons of expected performance with natural analogs or quantitative comparisons against regulatory criteria with complex analytical models), have shown that, for carefully selected sites, it is difficult to conceive of credible mechanisms for the loss of waste isolation.

Although additional steps of the multiattribute utility analysis are required to obtain an estimate of the overall postclosure performance for each nominated site, a comparison of the scores in Table 3-4 provides some immediate insights. For each postclosure period, the lowest base-case score given for any salt site for any scenario is as high or higher than the base-case score assigned to the Hanford site for scenario 1 (the nominal case). Thus, in the best collective judgment of the panel, the performance of the salt sites under disruptive conditions will be better (or at least as good) as the performance of the Hanford site under expected conditions. This is not to say that the postclosure performance of the salt sites is guaranteed to be superior to that of the Hanford site or that the releases that could occur from the Hanford site are large enough to be of concern. The high scores for the Hanford site are all 10. Thus, in the judgment of the panel, a repository at the Hanford site may perform better than any of the salt sites under any or all scenarios (since the low scores for the salt sites range from 8 to 4). However, because there is a fairly clear dominance relationship between the salt sites and the Hanford site, it can be expected that the quantitative measure developed to compare the overall postclosure performance of the sites

Table 3-4. High, base-case, and low scores for sites and scenarios[a,b]

Scenario[d]	Davis Canyon[c] 0–10	Davis Canyon[c] 10–100	Deaf Smith[c] 0–10	Deaf Smith[c] 10–100	Richton Dome[c] 0–10	Richton Dome[c] 10–100	Hanford[c] 0–10	Hanford[c] 10–100	Yucca Mountain[c] 0–10	Yucca Mountain[c] 10–100
1	10 10 8	10 10 8	10 10 8	10 9 7	10 10 8	10 10 8	10 8 4	10 7 4	10 10 5	10 9 5
2	10 9 5	10 9 5	10 8 5	10 8 5	10 9 6	10 9 6	10 6 2	10 6 2	10 8 2	10 8 2
3	NC		NC		NC		NC		NC	
4	NC		NC		NC		NC		NC	
5	NC		NC		NC		10 7 3	10 7 3	NA	
6	NC		NC		NC		9 6 2	9 6 2	NA	
7	NA		NA		NC		NA		NA	
8	NC		NC		NC		NA		NA	
9	NA		NA		NA		NA		NA	
10a	NC		NC		NC		NC		7 2 0	9 7 3
10b	NC		NC		NC		NC		7 3 0	10 7 2
11	NC		NC		NC		NC		NC	
12	10 9 6	10 9 6	10 9 6	10 9 6	10 8 4	10 8 4	NC		NC	
13	NA		NA		NA		NA		NA	
14	10 10 8	10 10 7	10 10 7	10 9 6	10 10 7	10 10 7	10 7 3	10 7 3	NA	

[a] Key: NA = scenario judged to have insignificant effect on releases; NC = scenario judged to be not credible.
[b] Higher scores are more desirable than lower scores.
[c] The numbers 0–10 and 10–100 represent 0 to 10,000 years after closure and 10,000 to 100,000 years after closure, respectively.
[d] See Table 3-2 for descriptions.

will rank the Hanford site lower than the salt sites. Analogous dominance arguments involving other pairs of sites cannot be made on the basis of the scores in Table 3-4.

3.5 MULTIATTRIBUTE UTILITY FUNCTION

The preceding sections described the low, base-case, and high scores assigned to quantify repository performance for each nominated site in the nominal case and for various disruptive scenarios. As described, judgmental scores were assigned to estimate performance in the first 10,000 years after closure and in the period 10,000 to 100,000 years after closure. This section discusses the various value judgments that are required for a logical aggregation of these scores to obtain an overall measure of the postclosure performance of each site. The value judgments for the analysis were made by the senior managers from the DOE's Office of Civilian Radioactive Waste Management (see Table A-4 of Appendix A).

Three steps are necessary to aggregate the various postclosure scores. First, it is necessary to account for the relative desirability of achieving higher versus lower scores for each performance measure. Single-attribute utility functions are used to quantify the desirability of various performance-measure scores. Second, the relative importance of achieving a given score in the first 10,000 years after closure as compared to achieving that same score in the next 90,000 years must be specified. The relative importance of performance in the two time periods is addressed by assigning scaling factors. Finally, the scores assigned to each site for various scenarios must be aggregated to obtain a single number, a so-called expected utility, that represents the expected postclosure performance of the site.

3.5.1 ASSESSMENT OF SINGLE-ATTRIBUTE UTILITY FUNCTIONS

To understand why single-attribute utility functions are needed, consider the definitions of the postclosure performance measures. It is clear that higher scores for the performance measures are more desirable, all other things being equal. For example, a site that scores 10 would be more desirable than an otherwise identical site that scores 8 for the same scenario, and a site that scores 8 would be more desirable than a twin that scores 6. It is not immediately clear, however, how much more desirable the higher-scoring site would be. For example, would a site that scores 8 be halfway between a site that scores 10 and a site that scores 6? The answer depends on two issues. The first is the relative magnitude of the releases that could occur at each site; the second is the level of concern about those releases.

The first issue—the relative magnitude of releases from sites with various scores—is easily resolved by examining the definitions of the performance-measure scales. As noted in Section 3.4, the scales are geometric. A site that scores 6 for the first 10,000 years is estimated to produce releases 100 times lower than the EPA limits; a site that scores 8 is estimated to produce releases 1000 times lower than the limits; and a site that scores 10 is estimated to produce releases 10,000 times lower than the limits. Thus, equal increases in scores (e.g., going from 6 to 8 versus from 8 to 10) do not produce equal increments in estimated releases. The marginal reduction in releases per unit increase in score decreases with increasing scores.

The second issue, the significance of various release magnitudes, requires value judgments. The single-attribute utility functions account for both the scales established for measuring performance (the first issue) and the value of achieving various levels of performance on those scales (the second issue).

The method used for assessing the single-attribute utility functions is the so-called midpoint method. The following notation will help to simplify the description of this method. Let y^{min} denote the smallest possible releases from a repository site (for simplicity, y^{min} was assumed to be zero) and let y^{max} denote the largest releases. In the assessment of a utility function for the first time period, y^{max} was taken to be ten times the EPA limits, in accordance with the performance-measure scale of Figure 3-3. The utilities of y^{max} and y^{min} are denoted by $U_1(y^{max})$ and $U_1(y^{min})$. Various release levels between y^{min} and y^{max} were then considered until one was found, denoted y', such that it was judged equally desirable to change a site with y^{max} releases to the level y' as it would be to change a site with y' releases to the level y^{min}. The release level y' is called the midpoint, or mid-utility point, because the utility of this level is midway between the utilities of the other two outcome levels (i.e., $U_1(y')$ is one half of $U_1(y^{min}) + U_1(y^{max})$). The same process was repeated to find other mid-utility points (e.g., the mid-utility point between y' and y^{max}) until enough points were identified to permit fitting a smooth curve. Finally, the curve was scaled so that the utility of zero releases (i.e., where $y = y^{min} = 0$), would be 100 and the utility of releases at the EPA limits (i.e., where $y = 1$), would be 0.

The same process was followed to obtain the utility curve for releases during the second period, 10,000 to 100,000 years after closure. In the second time period, releases could be as great as 100 times the EPA limits, whereby the definition of y^{max} was changed accordingly. Also, the utility curve was scaled so that the utility of releases equal to nine times the limit for the first 10,000 years would be zero.

The utilities obtained in the two encoding exercises were found to be very nearly proportional to the magnitude of releases. Figures 3-5 and 3-6 show the utilities obtained for the first and the second time periods, respectively, plotted as functions of cumulative releases during those periods. Because the deviations from linearity were very small, the DOE managers elected to assume direct proportionality between releases and utility. Specifically, linearity implies that

$$U_1(y_1) = 100(1 - y_1) \tag{3-1}$$

and

$$U_2(y_2) = 100(1 - y_2/9). \tag{3-2}$$

A linear relationship is an intuitive result, since it might be expected that postclosure releases would be roughly proportional to radiological health effects and that the desirability of a site would be directly proportional to decreases in radiological health effects.

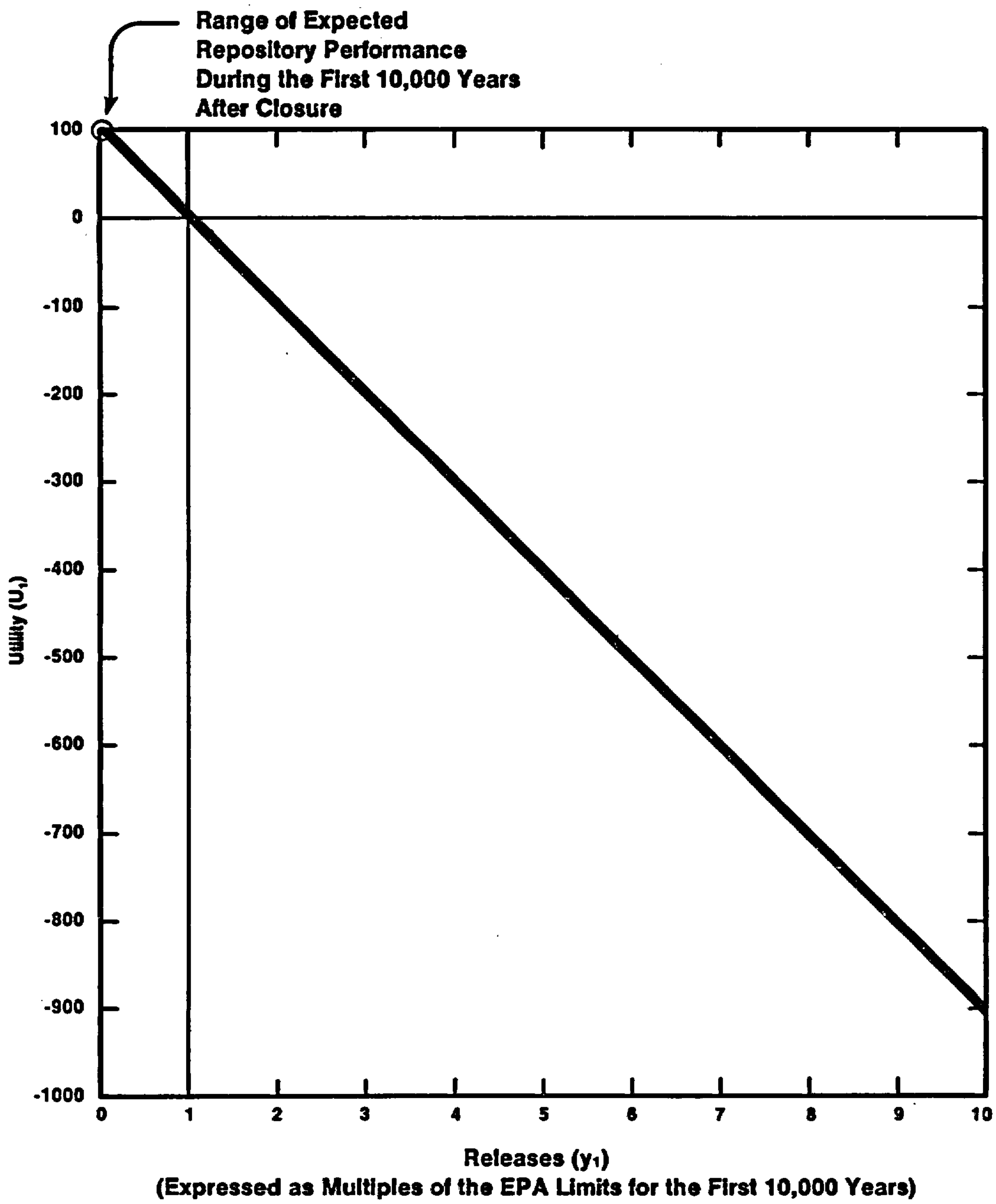

Figure 3-5. Assessed utility of cumulative releases during the first 10,000 years after repository closure.

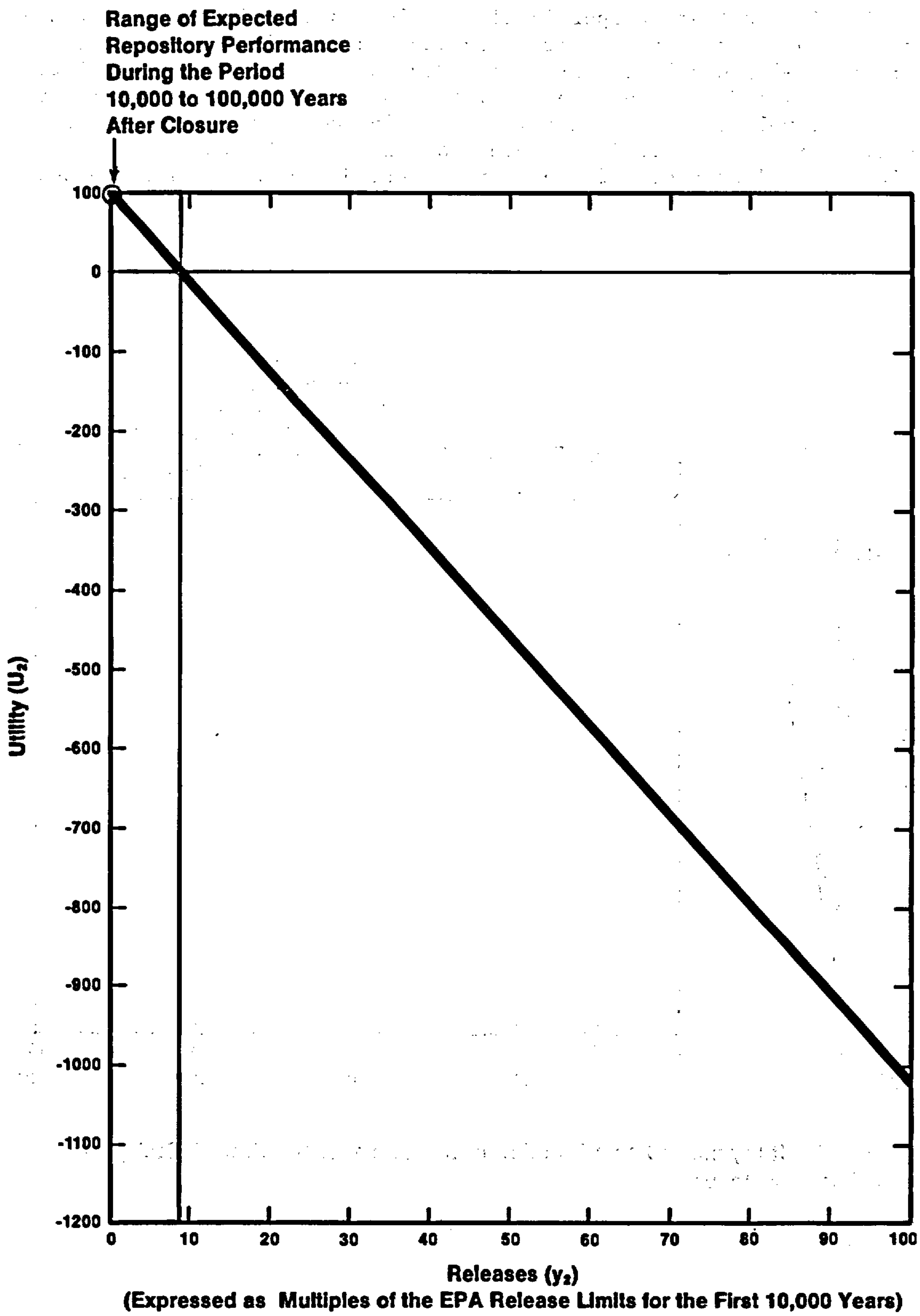

Figure 3-6. Assessed utility of cumulative releases during the period 10,000 to 100,000 years after repository closure.

When utilities that are proportional to releases are plotted as a function of scores that represent geometrically increasing releases, the curves shown in Figures 3-7 and 3-8 are obtained. Because of the geometric relationship between scores and releases, the utility function increases rapidly at first, but then levels out as further increases in score produce only very small reductions in the magnitude of releases. The utilities and the releases corresponding to various scores for each time period are shown in Table 3-5.

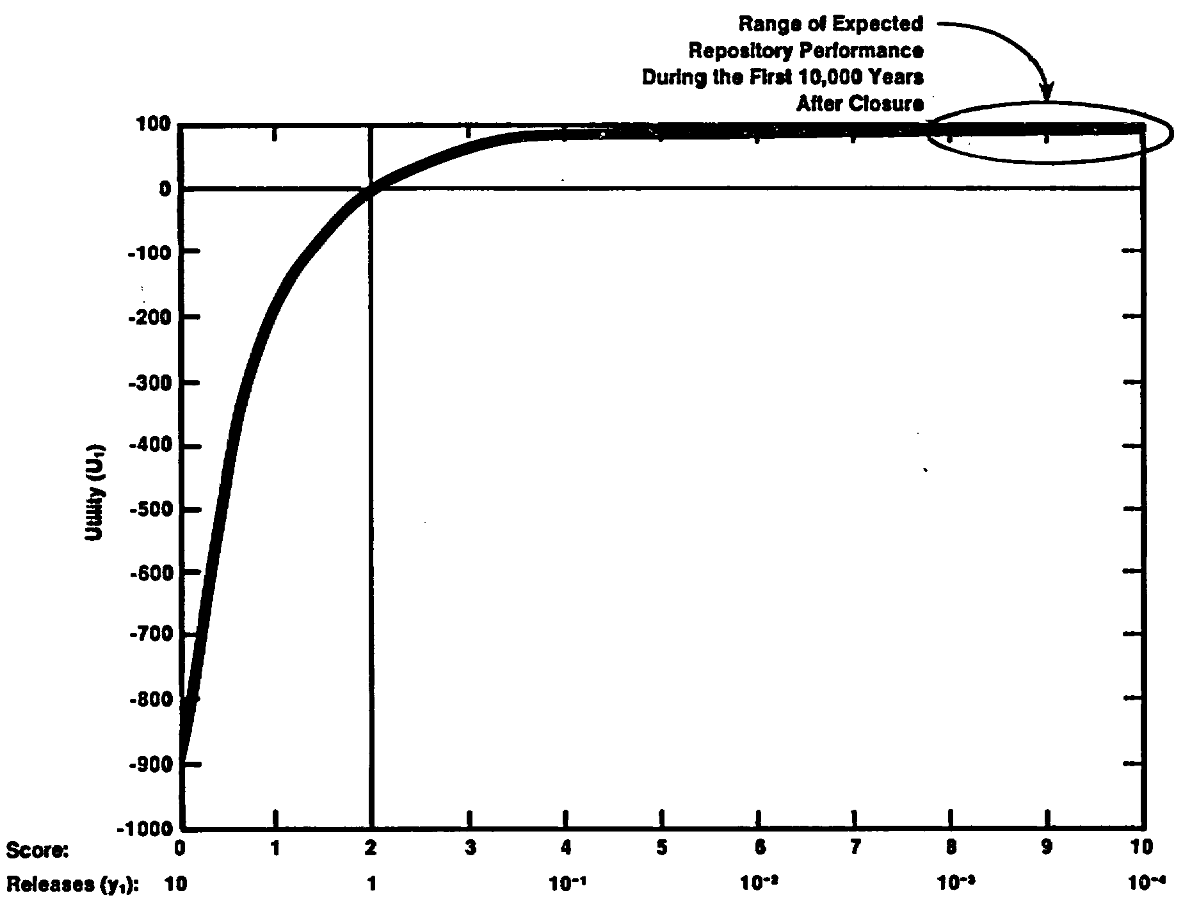

Figure 3-7. Utility plotted as a function of the score for the first 10,000 years after repository closure.

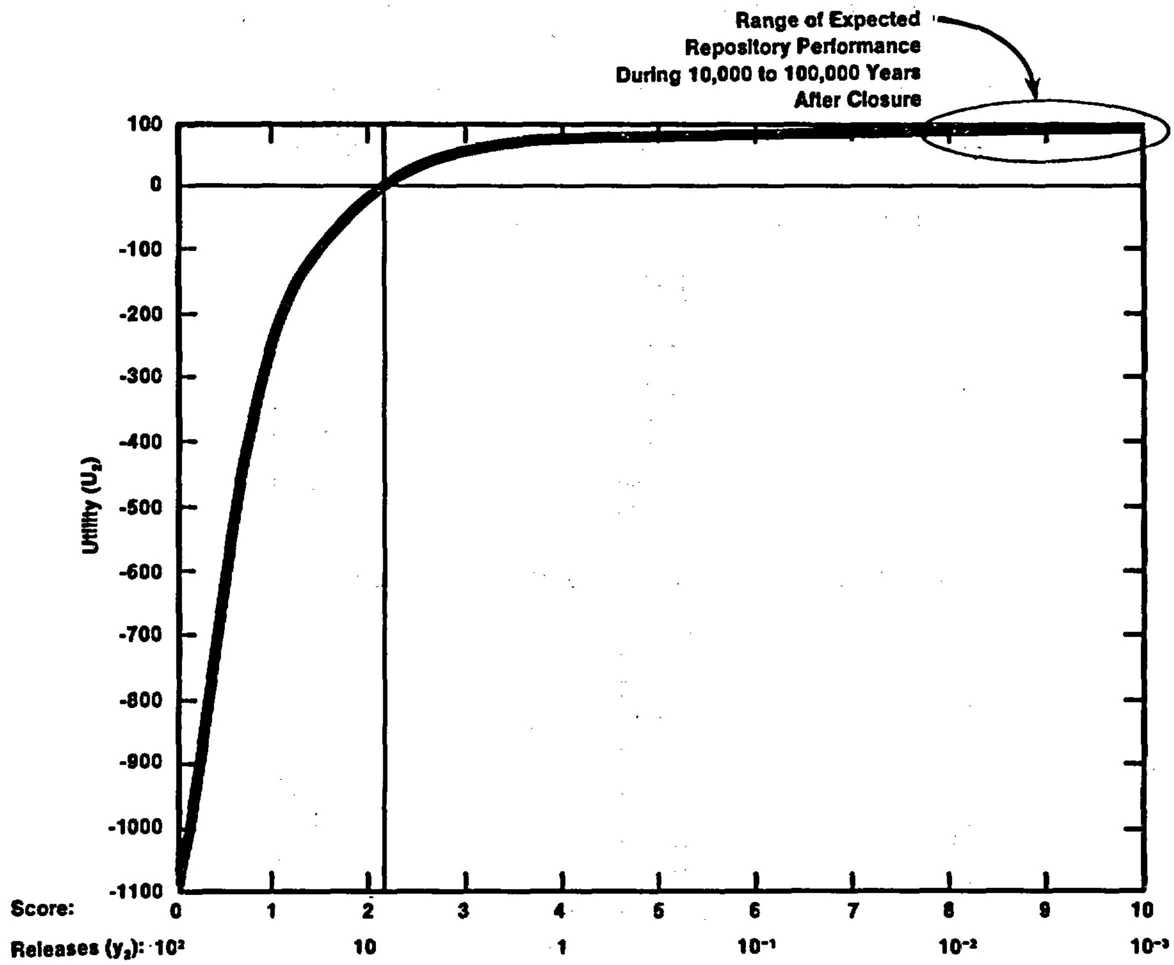

Figure 3-8. Utilities plotted as a function of score for the time period 10,000 to 100,000 years after closure.

As can be seen from Table 3-5, the policy judgment that the utility of postclosure performance in a given time period should be proportional to the cumulative releases during that time period has the effect of assigning a very high utility to any site receiving a score above 6. The reasoning underlying this judgment is that a site with releases that are 10,000 times lower than the EPA limits has little practical advantage over a site with releases that are 100 times lower. Although the use of a performance-measure scale that is geometric in releases allowed technical specialists the opportunity to make fine distinctions in the estimates of releases from repositories at the various sites, from a policymaking perspective these distinctions have little significance.

Table 3-5. Correspondence among scores, releases, and utilities

Score	Releases[a] (y_1, y_2)	Utility (U_1, U_2)
EARLY PERIOD: 0 to 10,000 YEARS AFTER CLOSURE		
—	0.0000	100.00
10	0.0001	99.99
9	0.0003	99.97
8	0.0010	99.90
7	0.0032	99.68
6	0.0100	99.00
5	0.0316	96.84
4	0.1000	90.00
3	0.3162	68.38
2	1.0000	0.00
1	3.1623	-216.23
0	10.0000	-900.00
LATE PERIOD: 10,000 to 100,000 YEARS AFTER CLOSURE		
—	0.0000	100.00
10	0.0010	99.99
9	0.0032	99.96
8	0.0100	99.89
7	0.0316	99.65
6	0.1000	98.89
5	0.3162	96.49
4	1.0000	88.89
3	3.1623	64.86
2.09	9.0000	0.00
2	10.0000	-11.11
1	31.6228	-251.36
0	100.0000	-1011.11

[a] Multiple of EPA limits for the first 10,000 years after repository closure.

3.5.2 ASSESSMENT OF SCALING FACTORS

The postclosure release estimates provide a measure of how well a repository at a given site is expected to perform under a given scenario in each of the time periods under consideration--the first 10,000 years and 10,000 to 100,000 years after closure. The utility functions translate the estimated releases into units of utility, or desirability. To obtain an overall measure of a site's postclosure utility, the various release estimates and utilities must be aggregated. The method of aggregation can be described in the following manner. Let $S_1, S_2, \ldots, S_m$ denote the scenarios to be considered at a given site. For a given scenario S_i, let $y_1(S_i)$ denote the estimated releases during the first 10,000 years. Similarly, let $y_2(S_i)$ be the releases estimated for 10,000 to 100,000 years after closure. Let $U_1[y_1(S_i)]$ and $U_2[y_2(S_i)]$ denote the utilities for the releases $y_1(S_i)$ and $y_2(S_i)$. The combined postclosure utility for a site given a scenario S_i is obtained from an equation of the form

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

where k_1 and k_2 are scaling factors. The linear additive form, which involves weighting and adding the utilities for the two postclosure time periods, may be justified from independence arguments, as described in Appendix G.

The parameters k_1 and k_2 in Equation 3-3 are scaling factors that reflect the relative values of performance against the first and the second postclosure objectives. The numerical values of the parameters can be interpreted as follows. The parameter k_1 is the increase in the overall postclosure utility that would be achieved by decreasing releases in the first period enough to increase by one unit the utility on the first performance measure. According to Equation 3-1, a reduction in releases equal to 0.01 of the EPA release limits would increase the utility of performance in the first time period by one unit. Hence, k_1 is the increase in the overall postclosure utility of a site that would result if that site's releases during the first time period were reduced by 0.01 of the limits specified by the EPA standards. Similarly, k_2 is the increase in the overall postclosure utility that would be achieved by decreasing releases in the second period enough to increase by one unit the utility on the second performance measure. By Equation 3-2, k_2 is the increase in the overall postclosure utility of a site that would result if that site's releases during the second time period were reduced by 0.09 (0.01 in each 10,000-year interval) of the EPA limits.

To obtain a range of reasonable values for k_1 and k_2, the DOE managers (Table A-4) were asked to estimate societal preferences for hypothetical performance outcomes. The considerations involved hypothetical sites that would perform relatively well in one time period but poorly in the other. For example, one comparison involved the following performance outcomes for hypothetical sites A and B: At site A, the cumulative releases during the first 10,000 years are 10,000 times lower than the EPA limits (a score of 10 for this period). In the second period, however, the cumulative releases at site A were 100 times higher than the EPA limits (a score of 0). In contrast, at site B, the cumulative releases during the first 10,000 years were equal to 10 times the limits (a score of 0), but the cumulative releases during the second period were 1000 times lower than the limits (a score of 10). The table below summarizes the comparison (the releases are given as fractions of the EPA limits).

	Period 1		Period 2	
Site	Release	Score	Release	Score
A	0.0001	10	100	0
B	10	0	0.001	10

Three contrasting opinions were presented for which performance outcome—that associated with site A or B—would be preferable. With one view, site A is preferable because it performs extremely well during the first 10,000 years, the period that is emphasized in the regulations governing geologic disposal. According to another view, however, site B is preferable because the combined release from the two time periods is approximately only one-tenth as great

(10.001 times the limits versus 100.0001 times the limits). According to the third view, sites A and B are roughly equally desirable. One argument supporting this last view is that the rate of release per unit time in each of the time periods is approximately equal.

If the third view is taken (that the two sites are equally desirable), values for the scaling factors can be derived as follows: From Equation 3-3 and Table 3-5, the postclosure utility of site A is

$$U^{A}_{post} = k_1U_1(10^{-4}) + k_2U_2(100) = 99.99k_1 - 1011.11k_2.$$

Similarly, the postclosure utility of site B is

$$U^{B}_{post} = k_1U_1(10) + k_2U_2(10^{-3}) = -900.00k_1 + 99.99k_2.$$

Because indifference between the two cases implies equal utility,

$$99.99k_1 - 1011.11k_2 = -900.00k_1 + 99.99k_2,$$

which implies that

$$k_1 = 1.111k_2.$$

If the scaling factors are normalized to sum to unity,

$$k_1 + k_2 = 1,$$

then

$$k_1 = 0.526 \quad \text{and} \quad k_2 = 0.474.$$

After considerable discussion among the DOE managers, the above values were adopted as base-case values for the scaling factors. To accommodate the alternative views, however, more-extreme values were adopted to provide a range for sensitivity analyses. At one extreme, it was argued that all weight should be given to the first time period. Thus,

$$k_1 = 1.0 \quad \text{and} \quad k_2 = 0.0$$

were selected as one extreme for sensitivity analysis. At the other extreme, it was assumed that a given magnitude of cumulative releases during the second period was just as undesirable as the same magnitude of cumulative releases in the first period. With this view, the following hypothetical site outcomes (with releases stated as fractions of the EPA limits) would be judged equally desirable:

	Period 1		Period 2	
Site	Release	Score	Release	Score
C	0.001	8	10	2
D	10	0	0.001	10

The utilities of sites C and D are

$$U^{C}_{post} = k_1U_1(10^{-3}) + k_2U_2(10) = 99.90k_1 - 11.11k_2$$

and

$$U^{D}_{post,t} = k_1U_1(10) + k_2U_2(10^{-3}) = -900.00k_1 + 99.99k_2.$$

Assuming indifference implies that the two utilities are equal, then

$$k_1 = 0.100 \quad \text{and} \quad k_2 = 0.900.$$

These values of k_1 and k_2 were used as the other extreme for sensitivity analyses.

3.5.3 SPECIFICATION OF THE MULTIATTRIBUTE UTILITY FUNCTION

According to the multiattribute utility theory, which is described in more detail in Appendix G, a measure of site desirability with respect to postclosure performance can be obtained by calculating the expected value of the postclosure utility, where utility is calculated from Equation 3-3. Mathematically, the expected utility can be expressed as

$$E(U_{post}) = p_1U_{post}(S_1) + p_2U_{post}(S_2) + \dots + p_mU_{post}(S_m), \quad (3\text{-}4)$$

where U_{post} (S_i) is the postclosure utility of the site for scenario S_i (computed from Equation 3-3) and p_i is the probability assessed for scenario S_i for the given site (where $i = 1,2,\dots,m$). Thus, the expected utility is obtained by weighting the postclosure utility of the site for each applicable scenario by the probability of the scenario and summing the results.

Equation 3-4 assumes a neutral attitude toward risk in the sense that the effect on the computed expected postclosure utility of a low-probability scenario is proportional to the product of the release and the probability of the scenario. However, many people are averse to risk: to avoid a possible loss, they would pay more than the probability times the magnitude of the loss (e.g., pay more than $5 to avoid a 5-percent chance of losing $100). Because of risk aversion, it is sometimes argued that low-probability scenarios with significant adverse consequences should be given greater emphasis than that provided by an expected-value calculation. It is possible to test whether the ranking of a set of options changes if a risk-averse, rather than a risk-neutral, attitude is assumed. The next section presents the numerical results of applying Equations 3-3 and 3-4 and includes tests of the sensitivity of these results to changes in attitudes toward risk, evaluations of site performance, and estimates of scenario probabilities.

3.6 RESULTS AND SENSITIVITY ANALYSIS

If the base-case probabilities in Table 3-3 are used for the appropriate scenarios and the base-case scores in Table 3-4 are used with Table 3-5 to estimate the releases that would occur for a given scenario, the expected releases for various time periods and the corresponding expected postclosure utilities for the sites are as given in Table 3-6. "Expected utilities" are the expected values of the utilities of the site. "Expected releases" are the expected values of releases; that is, the sum of the releases estimated for various scenarios, weighted by the probabilities of the scenarios. As indicated, all of the sites have very low expected releases and very high expected postclosure utilities. The Davis Canyon and the Richton Dome sites have the highest expected utility values of 99.99 and are ranked first. The Deaf Smith and the 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.

These high expected utility values can be compared with the corresponding utilities that would be calculated for the hypothetical sites used as benchmarks in the scales of Figures 3-3 and 3-4. Suppose, for example, that a site with the characteristics given a score of 4 in Figure 3-3 and a score of 4 in Figure 3-4 was evaluated. The computed base-case postclosure utility for that site would be 89.47. More generally, sites whose scores for the first and the second postclosure time periods (10,000 years and 10,000 to 100,000 years) are 10 and 10, 8 and 8, 6 and 6, 4 and 4, 2 and 2, and 0 and 0 would have base-case postclosure utilities of 100, 99.90, 98.95, 89.47, -5.27, and -952, respectively. Only the sites with the lowest pairs of scores, 0 and 0 as well as 2 and 2, would receive low postclosure utilities. This is because it is judged that only under these relatively poor site conditions are significant releases likely.

The differences in the computed base-case expected postclosure utilities can be traced to the different scenario probabilities and scores assigned in Tables 3-3 and 3-4. Because scenario 1 (the nominal case) is by far the most likely for each site, its scores have a dominant effect on the expected postclosure utilities. The ranking of the sites, in fact, exactly matches the order of the base-case scores assigned for this scenario. Scenario 2 (unexpected features) also has a significant effect because of its relatively high probability in comparison with the other scenarios. Because the base-case scores for scenario 2 are closely correlated with the base-case scores for scenario 1, the effect of the second scenario is to reinforce the differences in the expected performances estimated for the sites in the nominal case.

The expected postclosure utilities can be interpreted by recalling the relationship between the individual utilities for each postclosure period and the releases that occur during that period (Table 3-5). The fact that the Davis Canyon and the Richton Dome sites were computed to have expected postclosure utilities of 99.99 implies that these sites were judged essentially equal to a site whose cumulative releases are approximately 0.00011 of the EPA limits during each 10,000-year interval after repository closure for 100,000 years. The expected utilities for the Deaf Smith and the Yucca Mountain sites are only slightly lower. The computed utilities indicate a judgment that these sites are comparable to a site with releases approximately twice that given above (about 0.00023 of the EPA limits). The computed postclosure utility of 99.76 for the Hanford site indicates that it is estimated to be equal to a site with releases approximately 22 times higher (about 0.0024 of the EPA limits) than that given in the first instance above. The uniform releases per 10,000-year interval that would be assigned a utility equal to the expected utility for each site are called "equivalent releases" and are shown in Table 3-6. The utilities computed for the various sites are extremely high (close to 100) because the equivalent releases are only a small fraction of the EPA release limits.

Table 3-6. Computed base-case expected releases and postclosure utilities[A]

Site	Expected releases: 0-10,000 years[B]	Expected releases: 10,000-100,000 years[B]	Expected releases: 0-100,000 years[B]	Expected postclosure utility	Equivalent release per 10,000 years[A,B]
Davis Canyon	1.03×10^{-4}	1.03×10^{-3}	1.13×10^{-3}	99.99	1.09×10^{-4}
Deaf Smith	1.15×10^{-4}	3.26×10^{-3}	3.38×10^{-3}	99.98	2.33×10^{-4}
Richton Dome	1.04×10^{-4}	1.04×10^{-3}	1.15×10^{-3}	99.99	1.10×10^{-4}
Hanford	1.25×10^{-3}	3.32×10^{-2}	3.44×10^{-2}	99.76	2.41×10^{-3}
Yucca Mountain	1.17×10^{-4}	3.29×10^{-3}	3.40×10^{-3}	99.98	2.35×10^{-4}

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

Some indication of whether the differences in expected postclosure utilities are significant in relation to existing uncertainties can be found by exploring the sensitivity of the results to various assumptions. Sensitivity analyses are performed to determine (1) which parameters of the expected-utility equations (i.e., Equations 3-3 and 3-4) have the greatest effect on the expected utilities and rankings of the five nominated sites and (2) which parameters, when varied across their ranges of uncertainty, cause the base-case ranking of sites to change, thus indicating which assumptions or values could affect the ranking of the sites.

The key results of the various sensitivity analyses are shown in the figures to be presented in this section. Most of the figures show how various assumptions affect the expected postclosure utility for each site and the equivalent releases (releases per 10,000 years that would cause a site to have a utility just equal to the expected utility). In general, the sensitivity analyses indicate that the base-case ranking of the sites is robust in the sense of being relatively insensitive to uncertainties or value assumptions.

Figures 3-9, 3-10, and 3-11 show how the expected postclosure utilities for each site depend on basic uncertainties and value assumptions. Figure 3-9 shows the range of expected postclosure utilities as the scores for each site are simultaneously varied from the high to the low estimates in Table 3-4 with the probabilities of scenarios kept at the base-case estimates. Figure 3-10 shows the range of the expected postclosure utilities as the probabilities of disruptive and unexpected-feature scenarios are simultaneously varied from the high to the low estimates given in Table 3-3 with the scores kept at base-case values. Figure 3-11 shows the range of the expected postclosure utilities as scores and probabilities are simultaneously varied from optimistic assumptions (high scores for the sites and low probabilities for disruptive and unexpected-feature scenarios) to pessimistic assumptions (low scores for the sites and high probabilities for disruptive and unexpected-feature scenarios).

Figure 3-12 shows the effect of assuming increasing aversion to risk. To obtain these results, possible outcomes involving high releases were given greater weight through the use of an exponential function whose effect is determined by a parameter called the "risk-preference constant." Chapter 4 describes the method in more detail. When the constant is set to zero, no risk aversion is assumed, and the results are identical with the expected-value calculation. Decreasing the value for the coefficient below zero adjusts the utilities to account for greater aversions to the possibilities involving high releases. Because the base-case release estimates are low even for the scenarios involving unexpected features and disruptive processes and events, risk aversion does not significantly alter the relative utilities or change the site rankings. With high levels of risk aversion, Yucca Mountain is slightly less preferred because of the possibility of relatively high releases under the low-probability scenarios involving extrusive magmatic events. The y-axis in the figure is expressed in terms of equivalent releases.

Figure 3-13 shows the effect of changing the assumption that the single-attribute utility functions are linear in cumulative releases. The effect is to intensify (or reduce) the impact of scenarios, but the ranking of sites is not changed. Thus, if the utility function is curved in such a way that the marginal value of reducing releases is greater when releases are low than it is when they are high, the sites with smaller nominal releases attain more-favorable expected utilities. Sensitivity analysis shows that the effects of such curvatures on expected utilities are extremely small.

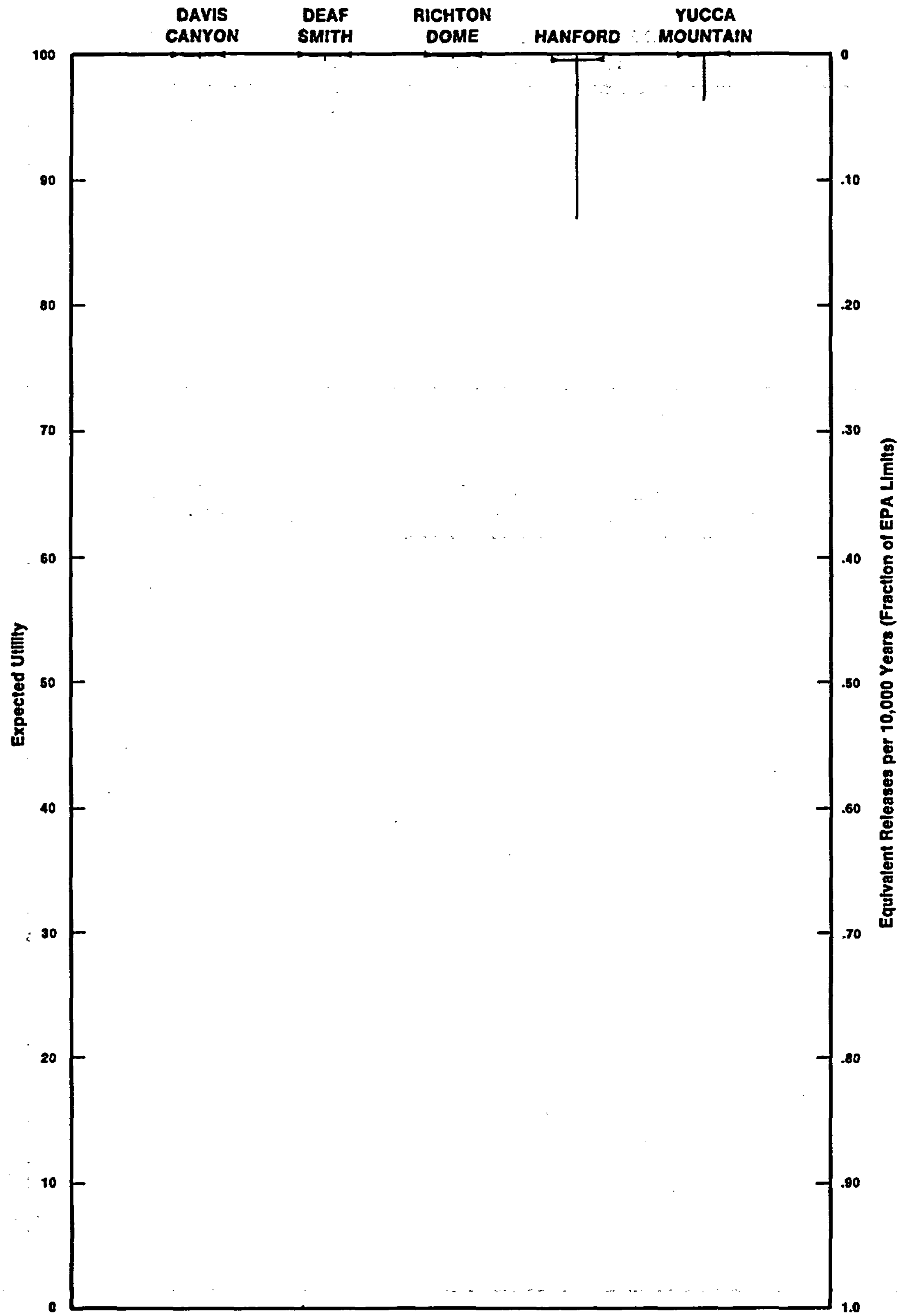

Figure 3-9. Sensitivity of the expected postclosure utility and the equivalent releases to variations in site scores from high to low judgmental estimates. Arrowheads indicate the base-case expected utilities.

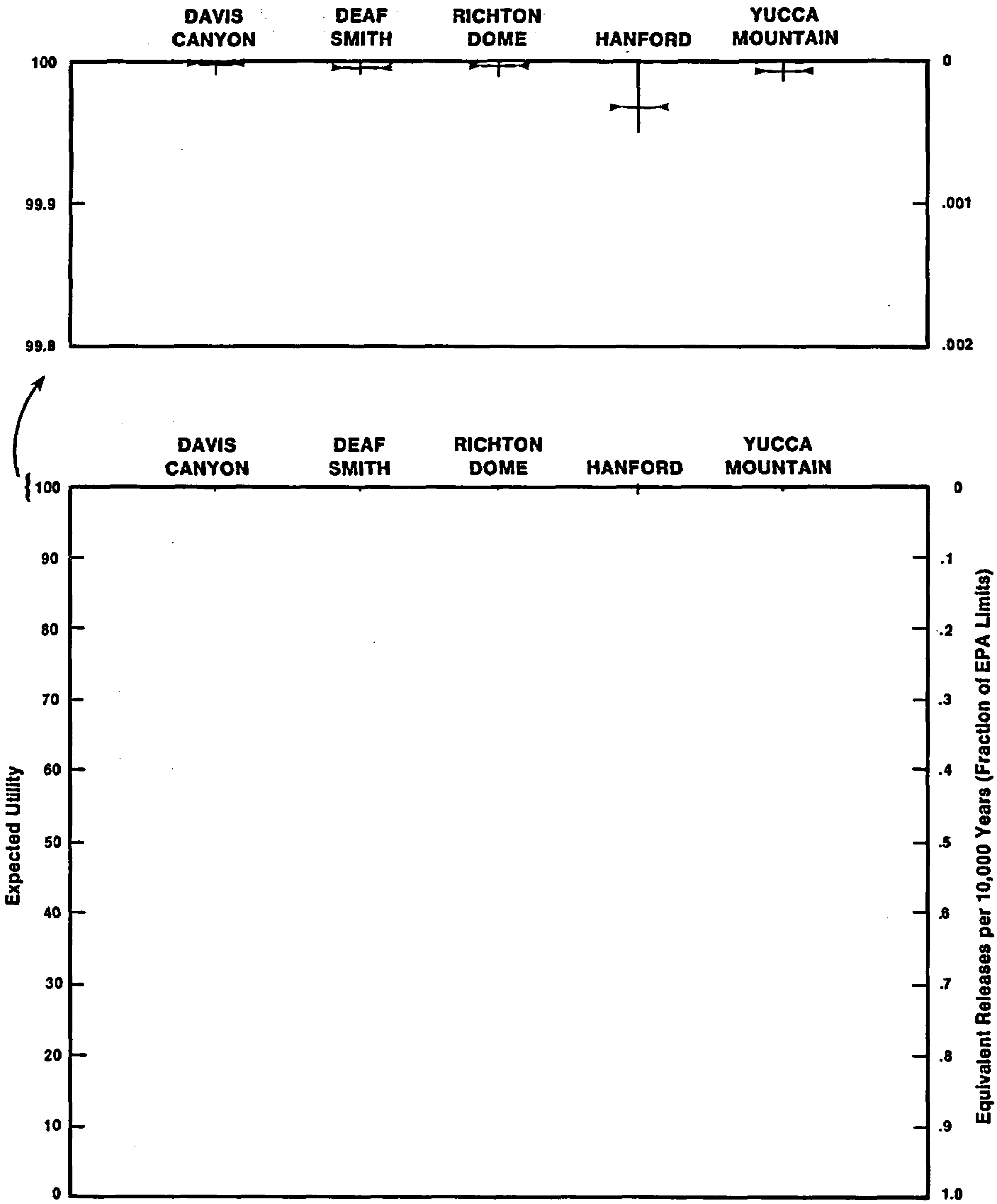

Figure 3-10. Sensitivity of the expected postclosure utility and the equivalent releases to variations in scenario probabilities for the sites. The figure at the top shows an enlargement of the extreme top of the scale (99.8 to 100). Arrowheads indicate the base-case expected utilities.

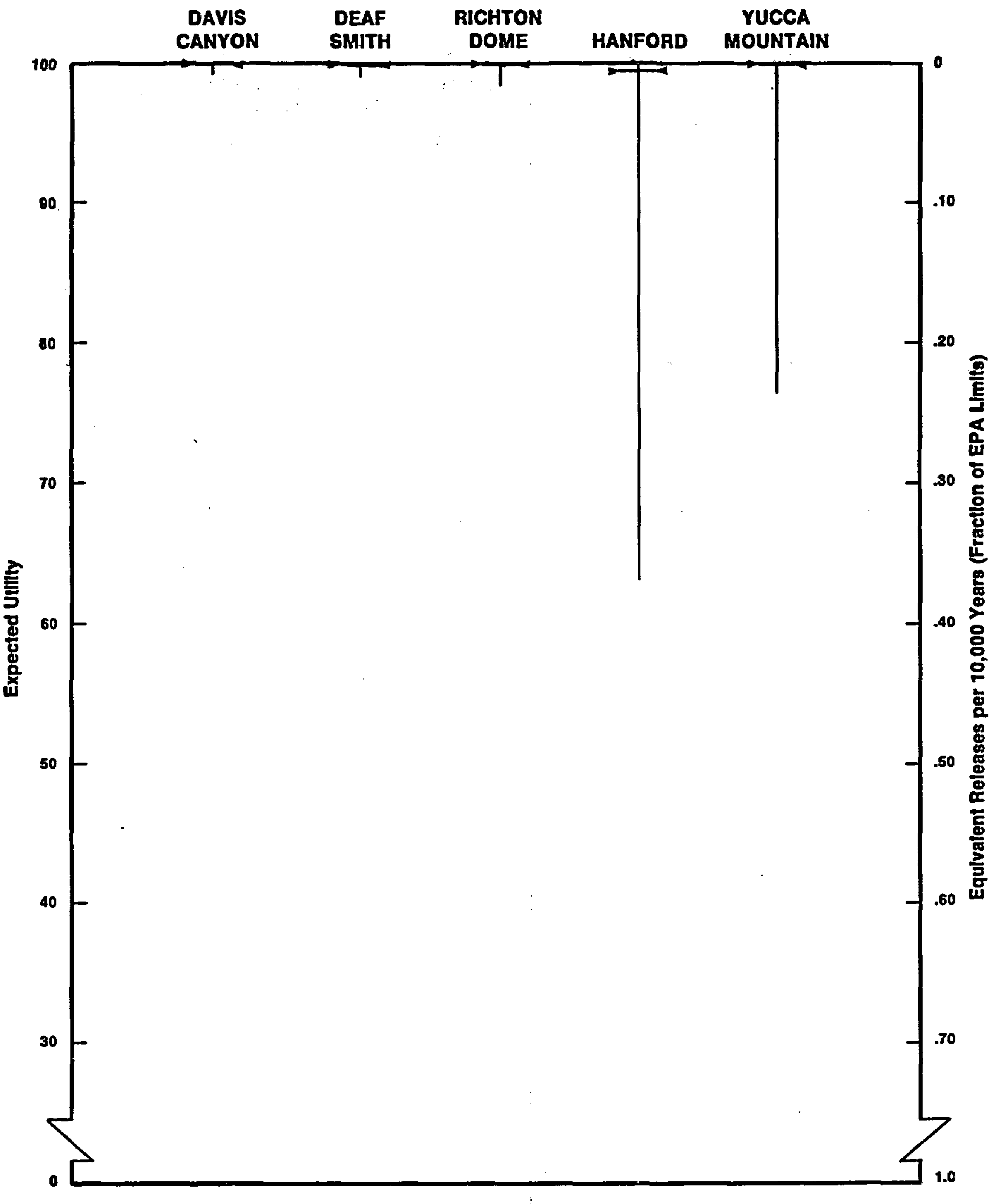

Figure 3-11. Sensitivity of the expected postclosure utility and the equivalent releases to variations in scores and scenario probabilities from optimistic (high scores and low probabilities for disruptive and unexpected-feature scenarios) to pessimistic (low scores and high probabilities for disruptive and unexpected-feature scenarios). Arrowheads indicate the base-case expected utilities.

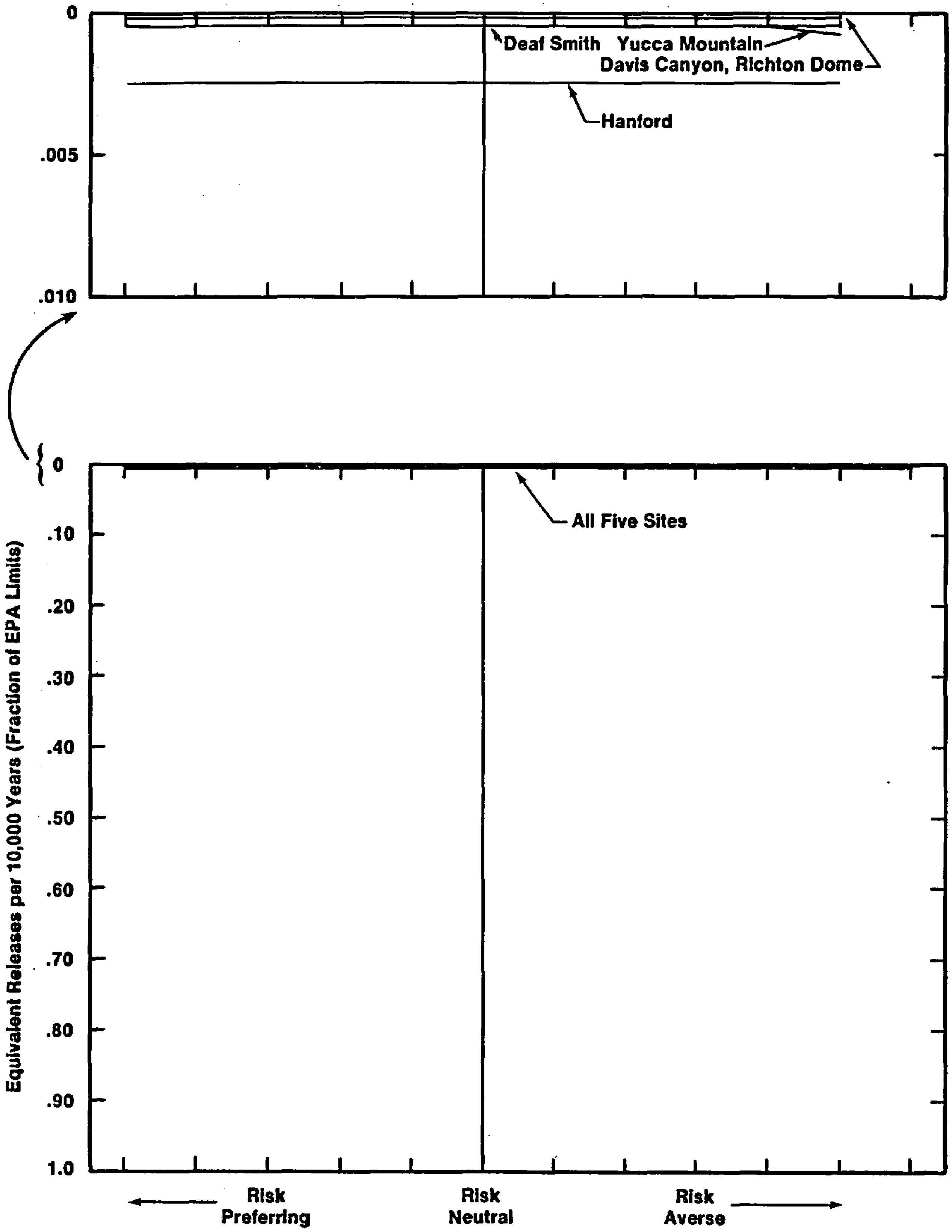

Figure 3-12. Sensitivity of postclosure certain-equivalent releases to risk attitude. The figure at the top shows an enlargement of the extreme top of the scale (0.010 to 0).

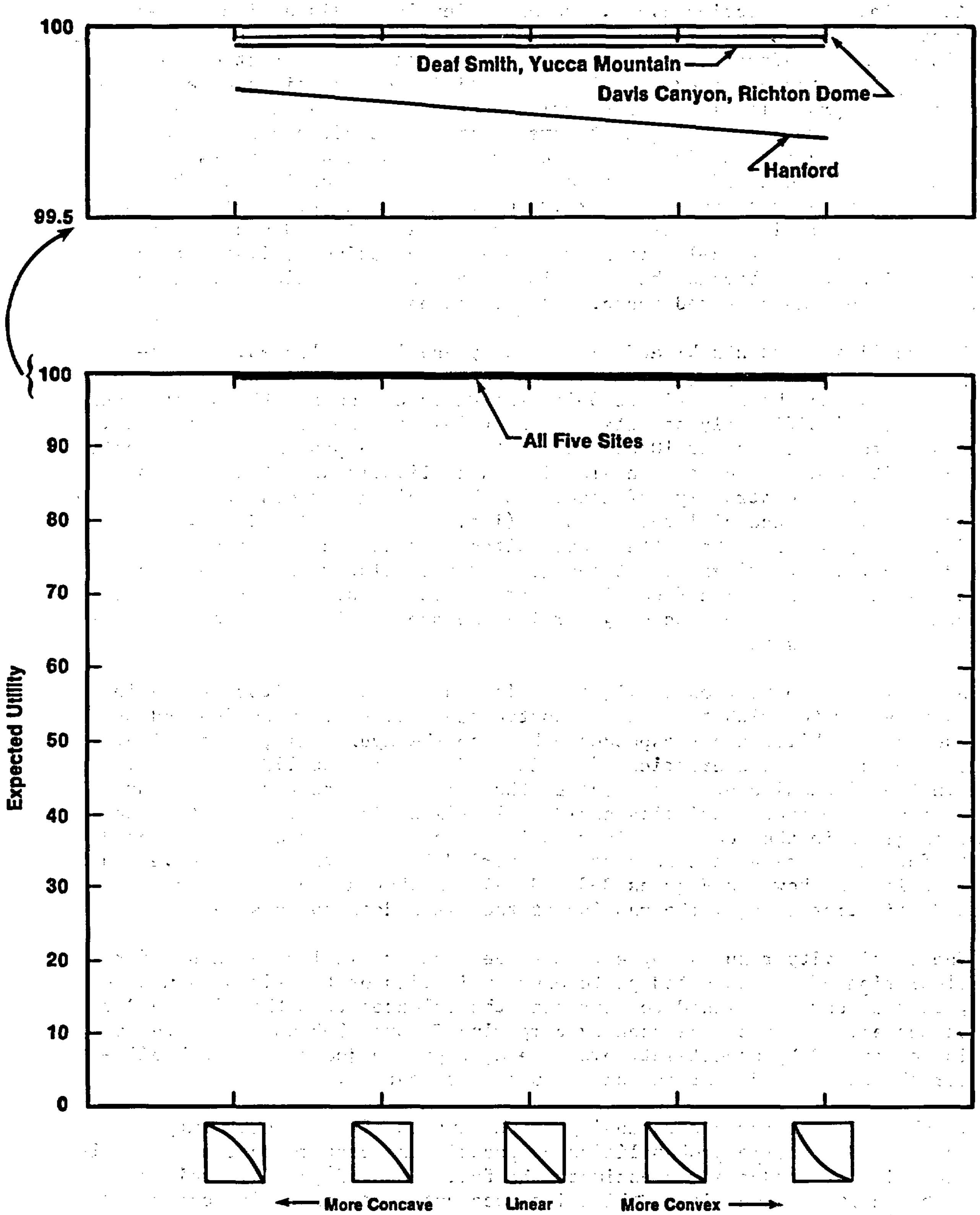

Figure 3-13. Sensitivity of the expected postclosure utility and the equivalent releases to variations in assumptions about the curvature of the single-attribute utility function. The figure at the top shows an enlargement of the extreme top of the scale (99.5 to 100).

As explained in Section 3.3.1, scenarios involving disruptive processes and events considered only the processes or events that might occur during the first 10,000 years after repository closure. To check the effect of relaxing this assumption, the expected postclosure utilities of the sites were recomputed with the probabilities of disruptive scenarios increased by a factor of 10. Such an assumption would tend to overestimate the effects of disruptive processes and events that might occur during the first 100,000 years because, although this period is 10 times as long, disruptions occurring 10,000 to 100,000 years after closure are unlikely to produce cumulative releases as large as they would if they were to occur in the first 10,000 years. The results, shown in Figure 3-14, thus provide a conservative estimate of the effect of disruptions beyond the first 10,000 years. As indicated, there is little effect on the expected postclosure utilities.

The scaling constants k_1 and k_2 for early and late releases, respectively, reflect a value judgment about the relative importance of early and late releases. As shown by Figure 3-15, the Davis Canyon and the Richton Dome sites are not significantly affected by the values of the scaling constants, since estimated releases per 10,000-year interval are approximately constant. The Deaf Smith and the Yucca Mountain sites are slightly affected, and the Hanford site is more strongly affected. As the scaling factors are changed to increase the importance of later releases (i.e., from $k_1 = 1$ and $k_2 = 0$ to $k_1 = 0.1$ and $k_2 = 0.9$), the latter three sites decrease in expected utility. However, the rankings do not change, and the relative differences between the sites are not significantly affected. The magnitudes of the effects are much less than that produced by varying the probabilities of scenarios or the scores for the sites.

As explained in Section 3.4.1, the releases from a repository at various sites were estimated with the aid of constructed scales (Figures 3-3 and 3-4). These scales establish a correspondence between the hydrologic, geochemical, and geomechanical characteristics of a site and the radionuclide releases. As noted in the discussion of these scales, the releases corresponding to any given set of site characteristics could be 10 times higher or lower than the estimates given in the scales. Figure 3-16 shows the effect on the expected utility for each site as the releases are varied by a factor of 10 above and below the levels shown in Figures 3-3 and 3-4. Although the differences in expected utilities change, the ranking of the sites does not change.

The sensitivity results suggest that the most critical uncertainty for the calculation of the expected postclosure utilities of the sites is uncertainty in the scores assigned to represent the releases from the sites under various scenarios. As can be seen by comparing Figures 3-9 and 3-11, the effect is compounded by uncertainty over the appropriate judgmental probabilities for the unexpected-feature and disruptive scenarios.

To obtain a clearer understanding of the impact of the uncertainty on site scores and scenario probabilities on postclosure performance, an approximate analysis was conducted to estimate the full range of possible releases that might occur at each site, taking into account uncertainty in scores and scenario probabilities. Figure 3-17 shows the estimated ranges within which the releases at, and the corresponding utilities of, each site are likely to fall. Although Figure 3-17 appears similar to the earlier figures, the bars

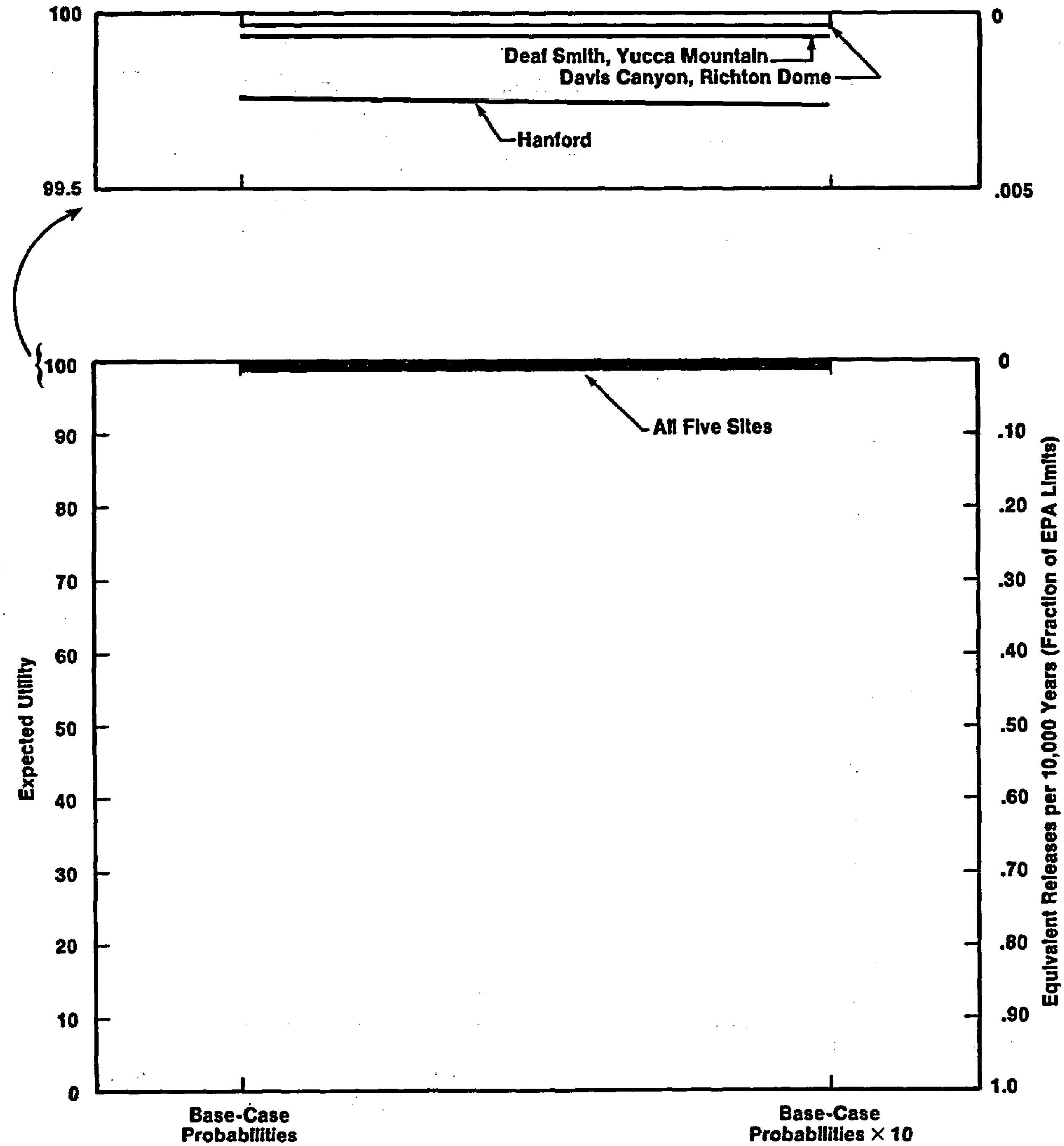

Figure 3-14. Sensitivity of the expected postclosure utility and the equivalent releases to scaling the probabilities of disruptive scenarios. The figure at the top shows an enlargement of the extreme top of the scale (99.5 to 100).

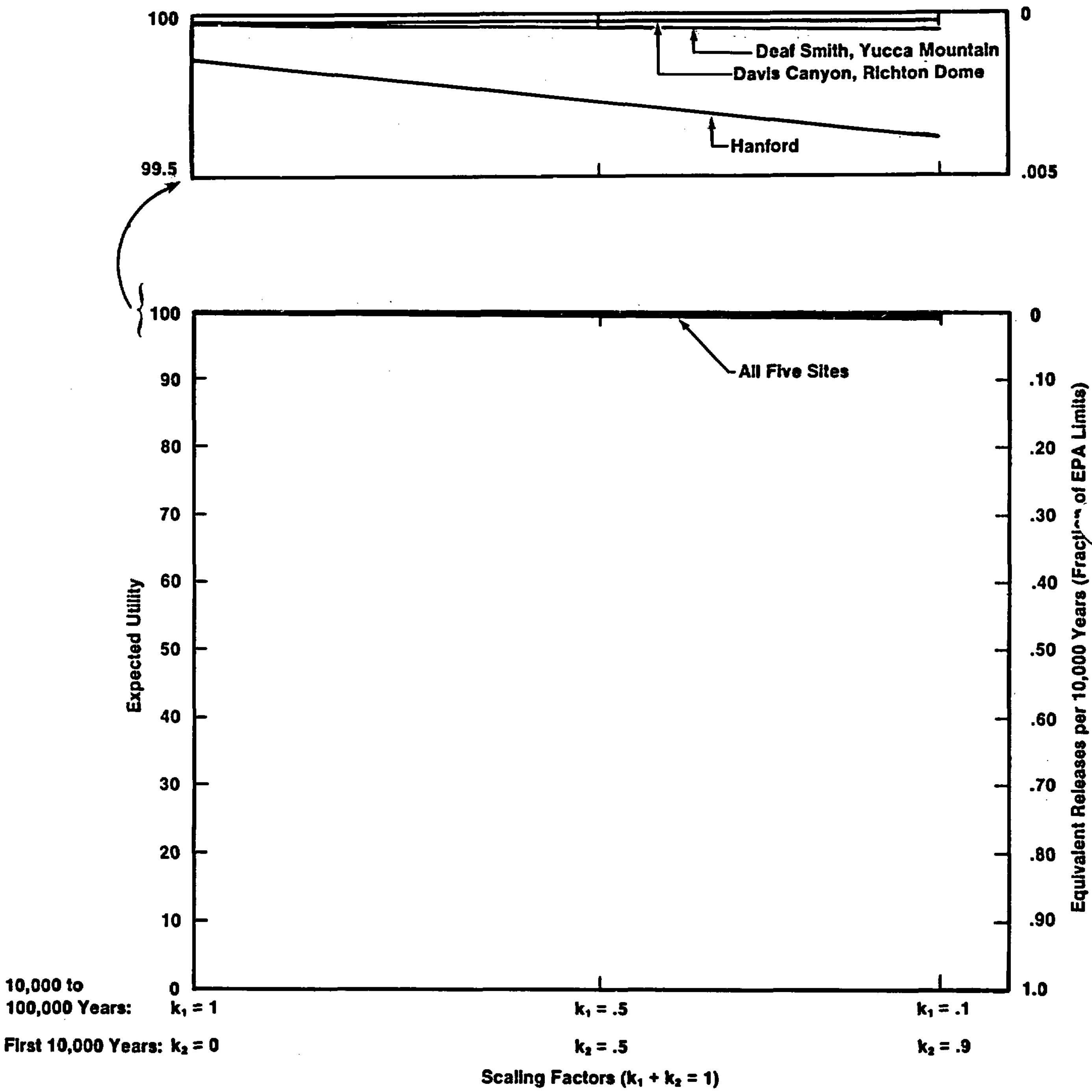

Figure 3-15. Sensitivity of the expected postclosure utility and the equivalent releases to variations in the values of the scaling factors. The figure at the top shows an enlargement of the extreme top of the scale (99.5 to 100).

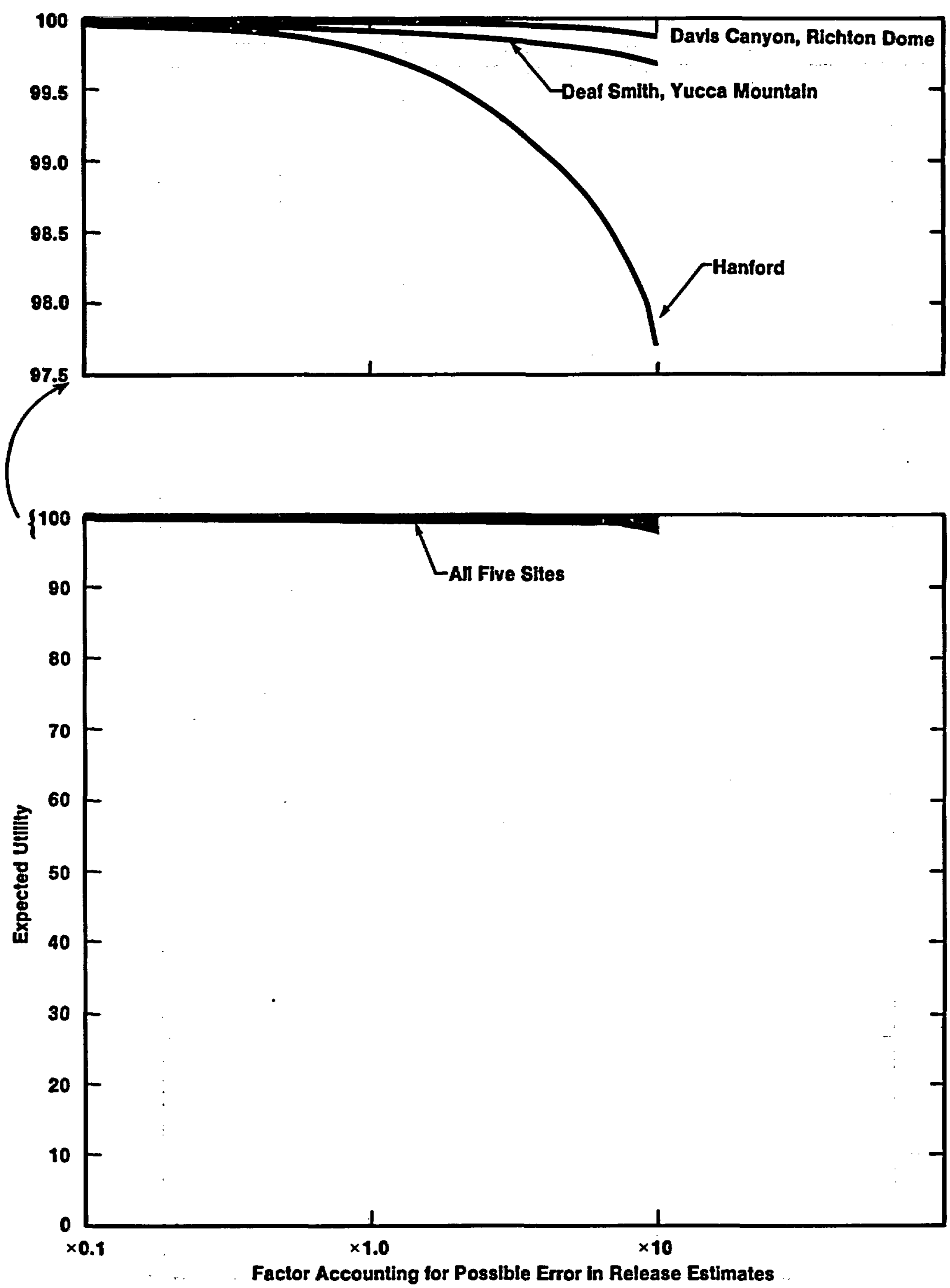

Figure 3-16. Sensitivity of the expected postclosure utility to uncertainty in correspondence between site characteristics and releases for the first 10,000 years and for the period 10,000 to 100,000 years. The figure at the top shows an enlargement of the extreme top of the scale (97.5 to 100).

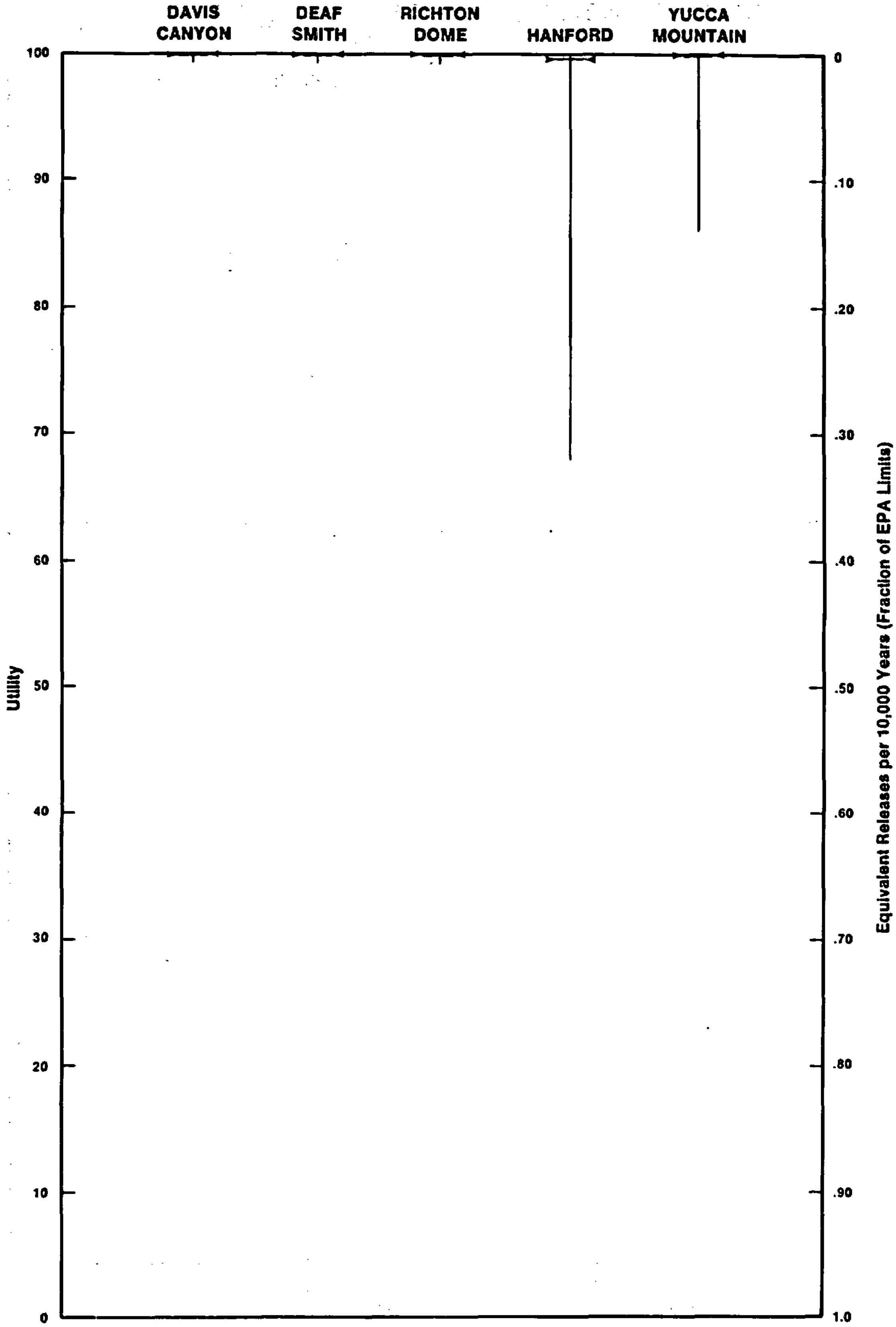

Figure 3-17. Ranges illustrating uncertainty in postclosure utilities and releases. Arrowheads indicate the base-case expected utilities. This figure should be considered together with Figure 3-18, which shows the relative likelihood of utility within a range of uncertainty.

indicate the likely range of actual utilities that might occur, rather than expected utilities wherein the low utility associated with each disruptive scenario is weighted by the low probability of the scenario's occurrence.

The approximate analysis that produced the results of Figure 3-17 consisted of the following steps. High, base-case, and low scores were assumed to have probabilities of .13, .74, and .13, respectively, for each site and scenario. These probabilities provide a more accurate discrete approximation to the uncertainty over scores (i.e., they more accurately approximate the variance) than probabilities of .05, .09, and .05, assuming that the continuous probability distributions on scores are bell-shaped. Similarly, probabilities of .13, .74, and .13 were assigned to each of the high-probability, base-case, and low-probability estimates for each scenario. The releases associated with the various combinations of scores were then evaluated, and each release was assigned a probability, assuming the independence of all probabilities.

The ranges shown in Figure 3-17 can be interpreted as approximate 98-percent confidence bands, derived according to the above assumptions. They encompass all but the highest and the lowest computed results, each of which accounts for 1 percent of the total probability. Although the uncertainty in the postclosure performance of the nominated sites is such that any of the utilities within the ranges are possible, outcomes near the high end of the ranges are much more likely. Figure 3-18 illustrates the general shape of the probability density functions that describe the relative likelihoods of various postclosure utilities. (The curve has been smoothed to eliminate discontinuities produced by the discrete approximation.) Because of the approximations and questionable assumptions underlying Figure 3-17 and 3-18 (especially independence), the numerical results should not be taken literally. Nevertheless, they strongly suggest that sites with a lower expected postclosure utility also tend to have greater uncertainty in postclosure performance.

3.7 CONCLUSIONS FROM THE POSTCLOSURE ANALYSIS

A number of conclusions can be derived from the base-case expected utilities, the ranges of uncertainty in releases, and the sensitivity analysis. Most striking is that all of the sites are expected to perform extremely well and are capable of providing exceptionally good waste isolation for at least 100,000 years after repository closure. As already mentioned, this finding is consistent with other studies of expected repository performance at carefully screened sites. When placed on a scale where a 0 can be interpreted as performance at the minimum level required by the primary-containment requirements of the EPA standards and 100 is perfection, all of the sites have expected utilities of 99.7 or higher. This corresponds to an assessment that all of the sites are as desirable as a site with an average release rate that is less than 0.003 of the EPA limits for 10,000 years.

The analysis shows that, under some unlikely disruptive scenarios and pessimistic assumptions, it is possible for a site to have releases that are a significant fraction of the EPA limits. At the salt sites, releases could be as high as one-tenth or so of the limits; at the nonsalt sites, releases could

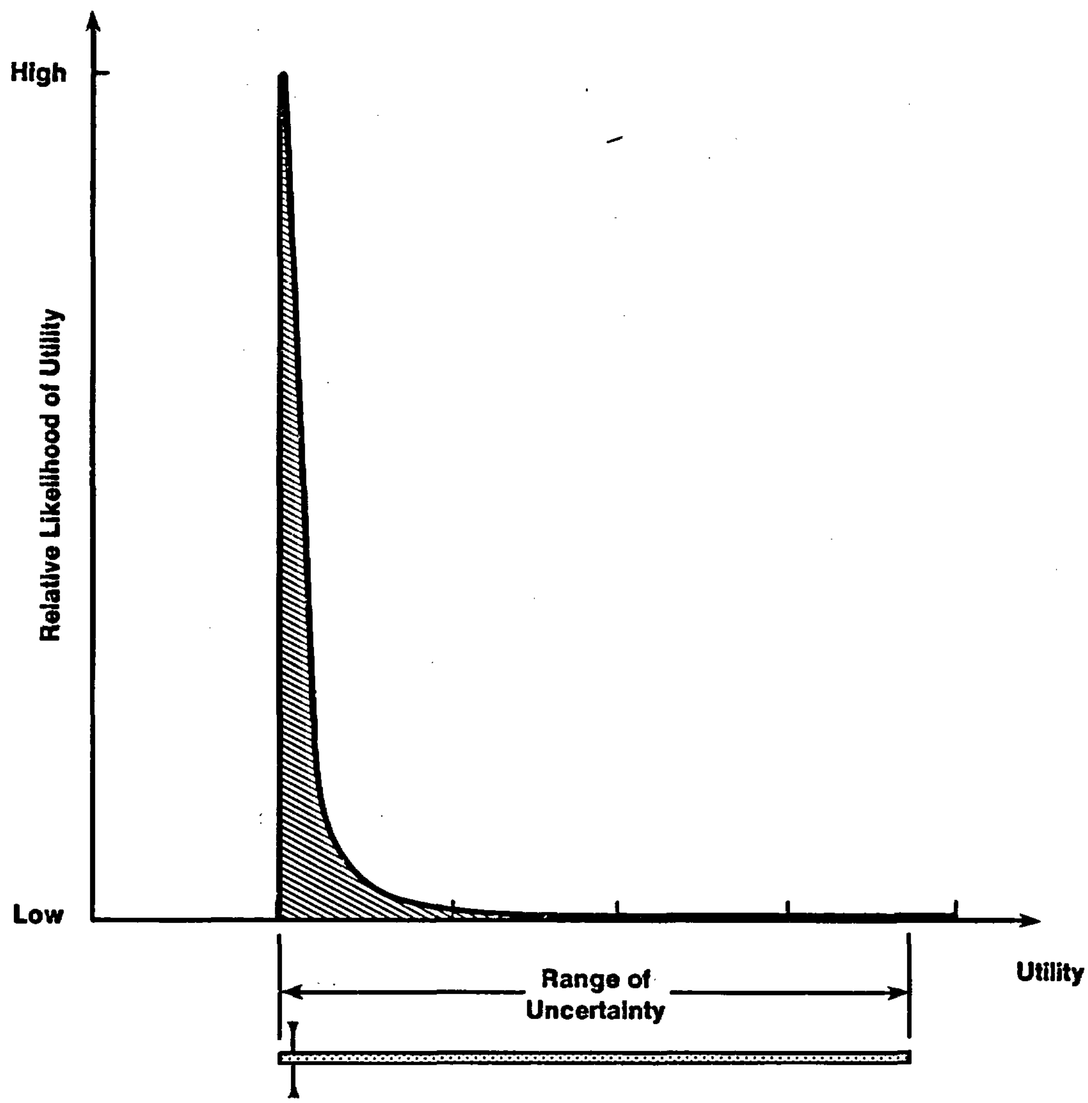

Figure 3-18. Approximate relative likelihood of achieving any given utility within a specified range of uncertainty (see Figure 3-17). Small arrowheads on the bottom bar indicate the base-case expected utility.

be equal to or greater than the limits. However, the probabilities of scenarios producing these higher releases are judged to be extremely low, only a few chances in a thousand at most.

From the relative ranking of the sites and estimates of uncertainty, it appears that the postclosure performance of a repository at the Hanford site would be slightly less favorable than that of a repository at the salt sites or at the Yucca Mountain site. The principal bases for this conclusion are technical judgments regarding the potential for waste dissolution, radionuclide travel time, and the possibility of the existence of unexpected features at the site. It must be kept in mind, however, that the release estimates are very low, and the utility differences among the sites are extremely small. The probabilities of the various possible postclosure releases and utilities (Figures 3-17 and 3-18) indicate that there is about one chance in five to one chance in ten that a repository at the Hanford site would actually have a lower level of releases than a repository at any of the salt sites.

Thus, there is greater confidence in the salt sites than in the nonsalt sites, and there is more confidence in the Yucca Mountain site than in the Hanford site. This is because of greater uncertainty in the performance of the nonsalt sites (especially the Hanford site) under expected conditions and a higher probability of significant disruptive scenarios and unexpected features at the nonsalt sites. Despite these differences, however, it is clear that the confidence in all sites is extremely high.

The postclosure rankings produced by the analysis are relatively insensitive to variations in assumptions, the uncertainty represented by the range of release estimates, and alternative value judgments. The differences in the expected postclosure utilities estimated for the sites, which quantify the relative postclosure desirabilities of the sites, are extremely small. Uncertainties not accounted for in the analysis, such as errors associated with the limits of human judgments or the possibility of unidentified mechanisms for releases, may be greater than the small postclosure differences identified by the analysis.

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Chapter 4

PRECLOSURE ANALYSIS OF THE NOMINATED SITES

This chapter presents a preclosure analysis of the five sites nominated as suitable for characterization. Section 4.1 presents the objectives defined for the evaluation of the sites. Section 4.2 defines a performance measure for each objective to indicate the degree to which the five sites achieve the objectives. Section 4.3 describes the performance of each site in terms of a set of performance measures. Section 4.4 discusses the multiattribute utility function assessed to integrate the ratings on the different performance measures into an overall evaluation of the sites. The results of the base-case evaluation and numerous sensitivity analyses are presented in Sections 4.5 and 4.6, respectively. Section 4.7 discusses the conclusions of the preclosure analysis of sites.

4.1 THE OBJECTIVES HIERARCHY

The perspective taken in this analysis is that the sites should be evaluated in terms of minimizing adverse preclosure impacts. This requires a set of objectives that characterize in a useful way the meaning of "adverse preclosure impacts." Specifically, the preclosure guidelines of 10 CFR 960.5 (DOE, 1984) specify the factors to be considered in evaluating and comparing sites on the basis of expected repository performance before closure. The preclosure guidelines specify three categories of factors: radiological safety; environment, socioeconomics, and transportation; and ease and cost of siting, construction, operation, and closure.

The preclosure guidelines were used as the basis for constructing the set of objectives represented by the objectives hierarchy in Figure 4-1. A combination of a top-down and bottom-up approach was used to develop the objectives hierarchy. In the top-down approach, the methodology lead group formulated an initial set of the most general objectives bearing on the ranking of the sites for the site-characterization decision. These general objectives, which were reviewed by members of DOE management and staff (see Appendix A), pertained to health and safety, environmental quality, socioeconomics, and costs. The general objectives were then made more specific by establishing what was meant by each, why it was important, how it might be affected by site selection, and so forth. As suggested in the professional literature, criteria of completeness, nonredundancy, significance, operationality, and decomposability were then applied to refine and improve the specification of lower-level objectives. The bottom-up approach involved working with the technical specialists (identified in Appendix A) to generate lists of objectives based on the siting guidelines and the "Supplementary Information" and Appendix IV to the guidelines. The identified objectives were then integrated into the objectives hierarchy developed from the top-down approach and approved by DOE management as the objectives of the preclosure analysis.

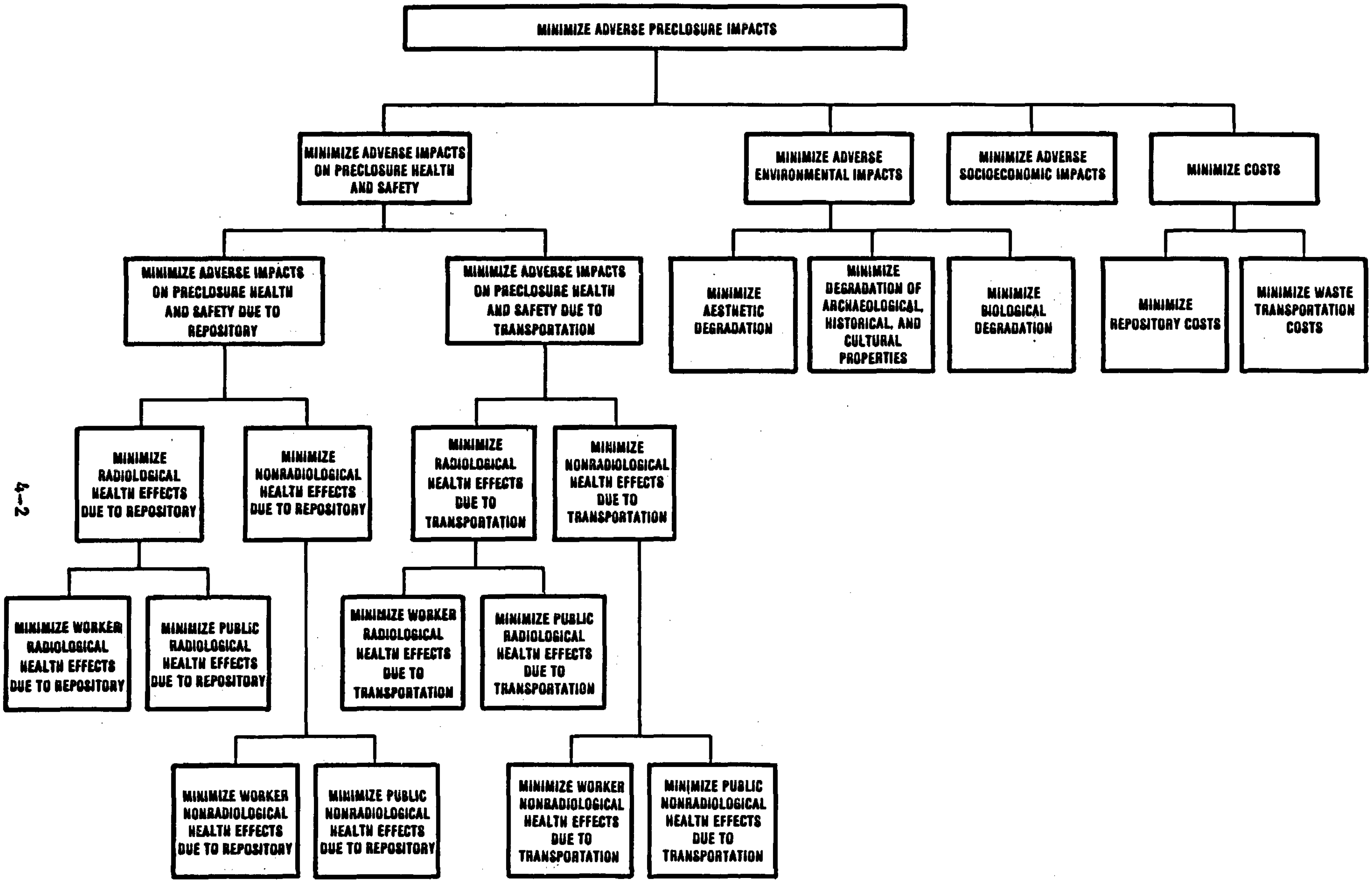

Figure 4-1. Preclosure objectives hierarchy.

As is readily evident, the minimization of preclosure impacts is defined to be equivalent to achieving to the extent practicable the following four major objectives:

- Minimize adverse impacts on health and safety before closure.
- Minimize adverse environmental impacts.
- Minimize adverse socioeconomic impacts.
- Minimize costs.

The meanings of each of these major objectives are made more precise by subobjectives and by the definition of the performance measures in Section 4.2.

Regarding preclosure health and safety, the possible impacts may be attributable to the repository itself or to waste transportation, they may be due to radionuclide releases or to nonradiological accidents and hazards, and they may be experienced by the public or by workers at the repository or in transportation. Thus, as shown in Figure 4-1, there are eight lowest-level objectives that correspond to the objective of minimizing adverse effects on preclosure health and safety. They range from minimizing the radiological health effects incurred by the public from the repository to minimizing the nonradiological health effects incurred by workers from waste transportation.

The environmental objective is divided into three more-specific subobjectives: to minimize adverse aesthetic impacts; to minimize adverse archaeological, historical, and cultural impacts; and to minimize adverse biological impacts. It is useful to recognize that objectives like "minimize air pollution" and "minimize the degradation of water resources," though important, are not explicitly included in the objectives hierarchy, because they are a means to achieving the fundamental objectives of the hierarchy. For instance, air pollution is a cause of nonradiological health effects in both the public and in workers, a cause of aesthetic degradation in rural areas, and a cause of biological impacts.

The socioeconomic objective is concerned with adverse impacts on the local communities surrounding a repository and disturbances of the lifestyles of their residents. These disturbances might be due, for example, to the influx of new residents or the use of local water resources.

The cost objective is divided into two subobjectives: to minimize the costs of the repository itself and to minimize the costs of waste transportation. As stated in the Nuclear Waste Policy Act, these costs are to be borne by the generators and owners of the waste.

4.2 PERFORMANCE MEASURES

For each of the lowest-level objectives in Figure 4-1, it is necessary to define a performance measure to indicate the degree to which the objective is achieved. For each site, repository performance before closure is then described in terms of impact levels for each performance measure. For example, the performance measure for the objective of minimizing repository costs is millions of dollars. The impact level for a given site might then be 8500 million dollars (i.e., 8.5 billion dollars). Collectively, the two cost impact levels indicate how well the overall cost objective is met. Similarly, the eight health-and-safety impacts collectively describe the degree to which each site meets the objective of minimizing adverse impacts on health and safety. Three impact levels are necessary to describe the environmental degradation for each site, and one level is used for adverse socioeconomic impacts.

As noted in Chapter 3, performance measures may involve scales of two different types: natural scales and constructed scales. Natural scales are those that have been established and enjoy common usage and interpretation; examples are costs in millions of dollars and numbers of fatalities. Constructed scales, on the other hand, are developed specifically for the problem. For instance, there is no natural scale for the objective "minimize aesthetic degradation." Hence, it is necessary to construct a scale that describes possible impacts. As will be readily apparent, health-and-safety objectives and cost objectives are measured by natural scales, whereas environmental and socioeconomic objectives are measured by constructed scales.

A listing of the 14 preclosure objectives and the associated performance measures is given in Table 4-1. For convenience in future reference, the performance measures are designated X_1 through X_{14} in the table.

4.2.1 PERFORMANCE MEASURES FOR HEALTH AND SAFETY

The eight performance measures for health and safety are the number of fatalities that might be attributed to the category characterized by the corresponding objective. For instance, with regard to the first objective of minimizing worker health effects due to radiation exposures at the repository, the performance measure is the number of cancer fatalities incurred by workers from radiation exposure at the repository.

All of the health-and-safety performance measures that are related to radiation exposure are numbers of cancer fatalities. The performance measures for nonradiological health-and-safety objectives are numbers of fatalities from accidents and possibly air pollution. (Air pollution is included mainly for completeness, as it is not expected to cause any fatalities.) The main reason for the nonradiological fatalities experienced by both workers and the public from the transportation of waste is traffic accidents.

Health-and-safety effects other than fatalities were not explicitly accounted for in the analysis. Since potential illnesses and injuries were felt to be strongly correlated with fatal health effects, the implications of their inclusion were examined in sensitivity analyses that greatly increased the weight on fatalities in the evaluation. These analyses, described in Section 4.6, indicate that the inclusion of nonfatal health effects would not lead to any additional insights or change any implications of the analysis.

The performance measures were selected by panels of technical specialists (see Appendix A) with expertise in health physics; repository design, construction, and operation; air pollution; and transportation. For most of the

Table 4-1. Objectives and performance measures

Objective	Performance measure
HEALTH-AND-SAFETY IMPACTS	
1. Minimize worker health effects from radiation exposure at the repository	X_1: repository-worker radiological fatalities
2. Minimize public health effects from radiation exposure at the repository	X_2: public radiological fatalities from repository
3. Minimize worker health effects from nonradiological causes at the repository	X_3: repository-worker nonradiological fatalities
4. Minimize public health effects from nonradiological causes at the repository	X_4: public nonradiological fatalities from repository
5. Minimize worker health effects from radiation exposure in waste transportation	X_5: transportation-worker radiological fatalities
6. Minimize public health effects from radiation exposure in waste transportation	X_6: public radiological fatalities from transportation
7. Minimize worker health effects from nonradiological causes in waste transportation	X_7: transportation-worker nonradiological fatalities
8. Minimize public health effects from nonradiological causes in waste transportation	X_8: public nonradiological fatalities from transportation
ENVIRONMENTAL IMPACTS	
9. Minimize adverse aesthetic impacts	X_9: constructed scale (see Table 4-2)
10. Minimize adverse archaeological, historical, and cultural impacts	X_{10}: constructed scale (see Table 4-3)
11. Minimize adverse biological impacts	X_{11}: constructed scale (see Table 4-4)
SOCIOECONOMIC IMPACTS	
12. Minimize adverse socioeconomic impacts	X_{12}: constructed scale (see Table 4-5)
ECONOMIC IMPACTS	
13. Minimize repository costs	X_{13}: millions of dollars
14. Minimize waste-transportation costs	X_{14}: millions of dollars

health-and-safety performance measures, detailed analytical models are available and were used to evaluate the impact levels at each site. The inputs to the models, shown in the influence diagrams (see Appendix E), and the results calculated by the models were reviewed over several months by the appropriate specialists. In those instances where the data required for the models are limited or not comparable from site to site, professional judgment was used to supplement calculations. This is explained in more detail in Appendix F.

4.2.2 ENVIRONMENTAL PERFORMANCE MEASURES

It was necessary to construct performance measures to indicate the degree to which the three environmental objectives are achieved. These constructed scales are presented in Tables 4-2, 4-3, and 4-4. The performance measure for aesthetic degradation is mainly concerned with the visual disturbances or the noise experienced by people living in or visiting the area of a site. The performance measure for impacts on archaeological, historical, and cultural properties is concerned with the number of such properties that would be affected and the significance of the impact. The possibility of mitigating such impacts is included in this performance measure, and it is assumed that such mitigation, where possible, would definitely occur. The performance measure for adverse biological impacts is concerned with adverse impacts on threatened and endangered species, on biologically sensitive species, or on the habitats of either; it is also concerned with any resultant threats to the regional abundance of the species.

A panel of technical specialists (see Appendix A) worked with decision analysts over several months to construct the scales for the performance measures. A first step in this process was the development of influence diagrams to identify the fundamental characteristics of a site that determine its ability to meet objectives (see Appendix E). These fundamental characteristics were then used as the basis for the constructed scales. The descriptions of the specific impact levels for the constructed scales were revised many times to ensure that the assignment of the impact levels could be traced and appraised by other professionals given the appropriate information.

As can be seen from Tables 4-2, 4-3, and 4-4, there are seven levels of impact for the performance measure describing adverse aesthetic impacts and six levels for the other environmental performance measures. The levels of impact are defined so that level 0 corresponds to no impact and higher levels designate increasingly adverse impacts.

4.2.3 SOCIOECONOMICS PERFORMANCE MEASURE

The socioeconomics performance measure is also a constructed scale concerned with the impact of the repository on the local communities, the infrastructure of those communities, the ability of people in those communities to retain the lifestyle they are accustomed to, and the indirect economic implications to persons in the local communities. It consists of a constructed scale of five levels (see Table 4-5). Level 0 corresponds to essentially no adverse socioeconomic impact, and higher levels designate a greater level of adverse impact.

The constructed scale was developed by a panel of technical specialists with expertise in socioeconomics and institutional analysis (see Appendix A) and decision analysts in a process that took several months. To guide the specification of the performance measure, an influence diagram (Figure E-12 in Appendix E) was constructed. An effort was made to make the descriptions of impact levels specific enough to represent and communicate distinct socioeconomic impacts of significance.

Table 4-2. Performance measure for adverse aesthetic impacts from the the repository and waste transportation

Impact level	Aesthetic impacts in the affected area[a,b]
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]Major effects are defined as the following:

- The affected area contains components of the National Park system, National Wildlife Refuge system, National Wild and Scenic River system, National Wilderness Preservation system, National Forest Lands, or a comparably significant State resource area, or an aesthetic resource that is unique to the area. The locations of such components are such that—
  - Four or more key observation points or sensitive-receptor areas within the resource area are on the line of sight or within audible distance of the project and/or
  - Some key observation points or sensitive-receptor areas on the line of sight or within audible distance of the project attract many visitors.
- The locations of residences, population centers, major vistas, natural or cultural landmarks, public recreation areas, or public highways are such that these points are on the project's line of sight and are within a visual setting that would significantly contrast with the project.
- The locations of residences, population centers, major vistas, natural or cultural landmarks, public recreation areas, or public highways are such that the project would be audible and would exceed established noise criteria.

[b]Minor effects are defined as the following:

- The affected area contains components of the National Park system, National Wildlife Refuge system, National Wild and Scenic River system, National Wilderness Preservation system, National Forest Lands, or a comparably significant State resource area, or an aesthetic resource that is unique to the area. The locations of such components are such that—
  - Three or fewer key observation points or sensitive-receptor areas within the resource area are on the line of sight or within audible distance of the project and/or
  - No key observation points or sensitive-receptor areas on the line of sight or within audible distance of the project attract many visitors.
- The locations of residences, population centers, major vistas, national or cultural landmarks, public recreation areas, or public highways are such that these points are on the project's line of sight but are within a visual setting that would not significantly contrast with the project.
- The locations of residences, population centers, major vistas, natural or cultural landmarks, public recreation areas, or public highways are such that the project would be audible but would not exceed established noise criteria.

Table 4-3. Performance measure for adverse archaeological, historical, and cultural impacts from the repository and waste transportation

Impact level	Impacts on historical properties in the affected area[a]
0	There are no impacts on any significant historical properties
1	One historical property of major significance or five historical properties of minor significance are subjected to adverse impacts that are minimal or amenable to mitigation
2	Two historical properties of major significance or ten historical properties of minor significance are subjected to adverse impacts that are minimal or amenable to mitigation
3	Two historical properties of major significance or ten historical properties of minor significance are subjected to adverse impacts that are major and cannot be adequately mitigated
4	Three historical properties of major significance or 15 historical properties of minor significance are subjected to adverse impacts that are major and cannot be adequately mitigated
5	Four historical properties of major significance or 20 historical properties of minor significance are subjected to adverse impacts that are major and cannot be adequately mitigated

[a] The performance measure is defined by the following:

- Historical property of minor significance: A historical property that is of local or restricted significance, but does not meet the criteria of significance for the National Register of Historic Places (e.g., a homestead or miner's cabin that is of local importance but does not meet the criteria of the National Register; an archaeological site that is representative of a period of time for which there are many examples).

- Historical property of major significance: A historical property that meets the criteria of significance 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) or a religious site highly valued by an Indian group (e.g., an Indian burial ground).

- Minimal impacts: Impacts that may alter the historical property, but will not change its integrity or its significance.

- Major impacts: Impacts that change the integrity or the significance of the historical property.

- Amenable to mitigation: The character of the historical property is such that it is possible to mitigate adverse impacts, reducing major impacts to minor or eliminating adverse impacts (e.g., impacts on an archaeological site that is significant because of the data it contains can be mitigated by excavating and analyzing those data; subsurface sites located within the controlled area may be protected under agreements made to guarantee that they will not be disturbed; a historical site can be adequately protected from vandals by erecting physical barriers).

- Not amenable to mitigation: The character of the historical property is such that impacts cannot be adequately mitigated because the value depends on the relationship of the historical property to its environment (e.g., a historical property of religious significance; a historical property that has value beyond the data contained; an archaeological site that is too complex for adequate excavation given state-of-the-art techniques).

Table 4-4. Performance measure for adverse biological impacts from the repository and waste transportation

Impact level	Biological impacts in the affected area
0	No damage to species of plants or wildlife that are desirable, unique, biologically sensitive, or endangered or to any biological resource areas that provide habitats for such species.
1	Damage to, or destruction of, individuals of desirable species or portions of biological resource areas that provide habitats for the species, but such species or resource areas are nonunique, nonsensitive, nonendangered, and common throughout the region.
2	Biologically sensitive species or resource areas are in the affected area. The damage to, or the destruction of, individuals of these sensitive species or portions of such resource areas does not threaten their regional abundance. Other affected biological resources are not unique in the region.
3	Threatened and endangered (T&E) species and/or habitats for T&E species are in the affected area. The damage to, or the destruction of, individuals of the T&E species or portions of the habitat does not threaten their regional abundance or Biologically sensitive species or resource areas are in the affected area. The damage to, or the destruction of, individuals of these sensitive species or portions of such resource areas threatens their regional abundance. Other affected biological resources are not unique in the region.
4	Threatened or endangered species and/or habitats for T&E species are in the affected area. The damage to, or the destruction of, individuals of the T&E species or portions of the habitats does not threaten their regional abundance and Biologically sensitive species or resource areas are in the affected area. The damage to, or the destruction of, individuals of these sensitive species or portions of such resource areas threatens their regional abundance. Other affected biological resources are not unique in the region.
5	Threatened and endangered (T&E) species and/or habitats for T&E species are in the affected area. The damage to, or the destruction of, individuals of the T&E species or portions of the habitats threatens their regional abundance and Biologically sensitive species or resource areas are in the affected area. The damage to, or the destruction of, individuals of these sensitive species or portions of such resource areas threatens their regional abundance. Other affected biological resources are unique in the region.

Table 4-5. Performance measure for adverse socioeconomic impacts from the repository and waste transportation

Impact level	Socioeconomic impacts in the affected area[a]
0	In-migrating population of 2000 persons is dispersed over a broad region with a population of 100,000. The public infrastructure[b] is adequate for repository-related growth. The transportation infrastructure[c] and the housing supply are also adequate. Because of the large population base and diverse lifestyles, values, and social structures, social disruptions are not expected. Direct and indirect employment of 1500 persons during repository operation, in a region with a total employment of 60,000, is not expected to lead to the economy of the area becoming overly dependent on the repository. Repository activities are not incompatible with existing land uses,[d] and no adverse impacts on water resources are expected. All land is State or federally owned, and no commercial, residential, or agricultural displacement is expected.
1	In-migrating population of 5000 persons is dispersed over an area with a population of 50,000. Moderate upgrading of the public infrastructure[b] and of the transportation infrastructure[c] is required to accommodate repository-related growth in the affected area. Moderate (2 percent) increase in housing supply is required to accommodate growth. Despite the expected population growth, in-migrants have lifestyles and values that are expected to match those of current residents; major social disruptions are not expected. Direct and indirect employment of 3000 persons during repository operation in a region with a total employment of 30,000 and a moderately diverse economy is not expectd to lead to a disruption of existing business patterns and economic dependence that cannot be avoided by applying standard economic-planning measures. Repository activities are not incompatible with existing land uses,[d] and no adverse impacts on water resources are expected. One-quarter of the land is privately owned, and minimal commercial, residential, or agricultural displacement is expected.
2	In-migrating population of 5000 persons is concentrated in a few communities in an area with a population of 50,000. Major upgrading of the public infrastructure[b] and of the transportation infrastructure[c] is required to accommodate repository-related growth in affected communities. A 10-percent increase in housing is also expected. More than a quarter of the residents have lifestyles and values that are unlikely to match those of in-migrants. Direct and indirect employment of 3000 during repository operation in a region with a total employment of 30,000 and a moderately diverse economy is not expected to lead to a disruption of existing business patterns and economic dependence that cannot be avoided by applying standard economic-planning measures.

Table 4-5. Performance measure for adverse socioeconomic impacts from the repository and waste transportation (continued)

Impact level	Socioeconomic impacts in the affected area[a]
2 (continued)	Repository activities are somewhat incompatible with existing land uses,[d] and minor impacts are expected; minor diversion of water resources from other activities is also expected.
	Half of the land is privately owned, and commercial, residential, or agricultural displacement is expected.
3	In-migrating population of 10,000 persons is concentrated in a few communities within an area with a population of 10,000. Major upgrading of the public infrastructure[b] and of the transportation infrastructure[c] is required to accommodate repository-related growth in affected communities. Considerable new housing (a 75-percent increase) is also expected.
	Affected communities have homogeneous lifestyles, values, and social structures that do not match those of the in-migrants; conflict between current and new residents is expected.
	Direct and indirect employment during repository operation of 5000 persons in a region with 5000 employees is expected to disrupt existing business patterns and to lead to substantial economic decline after the completion of waste-emplacement operations.
	Negative impacts are expected on existing land uses,[d] and minor diversion of water resources from other activities is expected.
	All land is privately owned, and commercial, residential, or agricultural displacement is expected.
4	In-migrating population of 10,000 persons is concentrated in a few communities in an area with a population of 10,000. Major upgrading of the public infrastructure[b] and of the transportation infrastructure[c] is required to accommodate repository-related growth in the affected communities. Considerable new housing (a 75-percent increase) is also expected.
	Affected communities have homogeneous lifestyles, values, and social structures that do not match those of the in-migrants; conflict between current and new residents is expected.
	Direct and indirect employment during repository operation of 5000 in a region with 5000 employees is expected to disrupt existing business patterns and to lead to substantial economic decline after the completion of waste-emplacement operations.
	Repository activities are incompatible with existing land uses,[d] and negative impacts are expected; major diversion of area water resources is likely, resulting in impacts on development in the affected area.
	All land is privately owned, and commercial, residential, or agricultural displacement is expected.

[a] Socioeconomic impacts equivalent to those listed in the table.
[b] The public infrastructure includes schools; medical facilities; police and fire services; water, sewer, and solid-waste systems; and recreation facilities.
[c] The transportation infrastructure includes roads, public transportation facilities, and the like.
[d] Examples of existing land uses are agricultural and residential uses, uses related to tourism, and uses related to local recreation.

4.2.4 COST PERFORMANCE MEASURES

The repository costs include the cost of siting, construction, operation, closure, and decommissioning. These activities will take place over a period of approximately 80 years. Transportation operations will span about 30 years, starting in 1998. The cost performance measures are millions of nondiscounted dollars for the repository and for waste transportation. Nondiscounted costs rather than discounted costs were chosen as performance measures because, for various reasons, the latter would not produce more insights from the analysis (see Section F.4.1). The reasons include large uncertainties about inflation rates and component escalation costs, the time when expenditures are made, and the appropriate discount rate.

Analytical models were used to estimate the costs of repository construction and operation and of transportation operations for each of the sites. Technical specialists with expertise in these areas reviewed both the data used in the models and the results--again over a period of several months. The specialists are identified in Appendix A, and the models are described in Appendix F.

4.3 DESCRIPTIONS OF POSSIBLE SITE IMPACTS

The possible impacts for each of the five sites for each of the 14 performance measures are presented in Table 4-6; both a base-case estimate and a range consisting of a high estimate and a low estimate are given. The base case is meant to describe the expected performance of a given site with respect to a given performance measure. Because there is uncertainty about the possible impacts, the range is included to indicate the significance of that uncertainty. The ranges were determined with the intent that they would have a 90-percent chance of encompassing the actual impacts exerted by a repository at the site. Consider, for instance, the repository-cost performance measure for the Yucca Mountain site in Table 4-6. The base-case estimate is 7500 million dollars (i.e., 7.5 billion dollars), and the range is from 4875 to 10,125 million dollars. This means that, if a repository is eventually developed at Yucca Mountain, the current judgment is that the estimated cost of construction and operation will have a 90-percent chance of falling between 4875 and 10,125 million dollars. Very brief comments on the base-case impacts and their uncertainties are presented below. The impacts are based on information in the environmental assessments of the five nominated sites (DOE, 1986a-e). Details on the logic underlying the estimates are provided in Appendix F.

The five panels of technical specialists who developed the preclosure performance measures also estimated the impacts for all five sites. The process of estimating the site impacts against each performance measure began in mid-December 1985 and continued through March 1986. A first step was the gathering of a consistent set of site data from the environmental assessments, using the previously developed influence diagrams and performance measures as guides. "Consistent set" means a common set of assumptions, level of detail, level of conservatism, etc. Workshops were then held to generate initial estimates of site impacts and the ranges. Details of the process used to generate the final estimates of site impacts reported in Table 4-6 varied somewhat from panel to panel. Individual panel members in some instances wrote justifications for the

Table 4-6. Base-case estimates and ranges of site impacts[A]

Performance measure	Richton Dome	Deaf Smith	Davis Canyon	Yucca Mountain	Hanford
X_1 = repository-worker radiological fatalities	2 (<1-4)	2 (<1-4)	2 (<1-4)	4 (<1-9)	9 (2-17)
X_2 = public radiological fatalities from repository	0.7 (0.3-1.5)	0.5 (0.1-1)	<0.1 (<0.1-0.2)	<0.1 (<0.1-<0.1)	0.7 (<0.1-1.5)
X_3 = repository-worker non-radiological fatalities	27 (17-36)	29 (19-39)	27 (17-36)	18 (12-24)	43 (28-58)
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	0.52 (0-0.73)	0.64 (0-0.90)	0.73 (0-1.0)	0.81 (0-1.1)	0.9 (0-1.3)
X_6 = public radiological fatalities from transportation	2.4 (0-3.4)	2.9 (0-4.1)	3.5 (0-4.9)	4.1 (0-5.7)	4.3 (0-6.1)
X_7 = transportation-worker nonradiological fatalities	1.3 (0.6-2.1)	1.6 (0.73-2.6)	2.1 (0.96-3.4)	2.5 (1.1-4.0)	2.7 (1.2-4.3)
X_8 = public nonradiological fatalities from transportation	5.3 (2.4-8.5)	6.7 (3.1-10.8)	8.4 (3.9-13.5)	10.2 (4.7-16.4)	11.0 (5-17.7)
X_9 = aesthetic impacts (see Table 4-2)	4 (1-5)	4 (3-5)	6 (6-6)	4 (1-5)	1 (1-2)
X_{10} = archaeological, historical and cultural impacts (see Table 4-3)	0.5 (0-1)	1 (0-2.5)	3 (2.5-5)	2 (2-3.5)	0.5 (0.5-3)
X_{11} = biological impacts (see Table 4-4)	2.67 (2-3.5)	2.33 (1.5-3)	3.5 (2.67-4.5)	2 (1-2.67)	2.33 (1-3.5)
X_{12} = socioeconomic impacts (see Table 4-5)	2 (1-3)	1.67 (1-3)	2 (1.33-3)	0.67 (0.33-2)	0.33 (0-0.67)
X_{13} = repository cost (millions of dollars)	9000 (5850-12,150)	9500 (6175-12,825)	10,400 (6760-14,040)	7500 (4875-10,125)	12,900 (8385-17,415)
X_{14} = transportation cost (millions of dollars)	970 (260-2040)	1120 (300-2350)	1240 (330-2600)	1400 (380-2940)	1450 (390-3040)

[A]Ranges are given in parentheses.

initial estimates of impacts and then shared drafts with the other members of the panel. In some cases additional workshops were held to discuss the bases for the estimates or, more simply, comments were provided to the lead panel member.

The initial estimates were in many cases revised and the bases refined over the course of several months. In most cases a group consensus was achieved on the estimates of the base-case impacts and the ranges. If consensus was not achieved, differences in opinion over the appropriate estimates were used to set the range of impacts. In other instances--for example, for those performance measures where detailed, well-established analytical models could be used to calculate impacts--the full panel was able to reach consensus on the appropriate levels of impacts at one workshop. The remainder of the time was spent checking the data for the models, the assumptions, etc., and in writing and refining the reasoning for the estimates of site impacts.

4.3.1 HEALTH-AND-SAFETY IMPACTS

4.3.1.1 Repository

Workers at the repository receive radiation doses directly from the natural radioactivity of the rock and also from repository operations. From the number of workers involved in each of these situations, the expected radiation emitted, and assumptions about ventilation, the number of cancer fatalities attributable to the exposure of workers to radiation in the repository was calculated. The assumed dose-effect relationship is that 280 cancer fatalities are caused by every million man-rem of population dose (i.e., the sum of the individual doses received by all the members of a population). As discussed in Appendix F, a different dose-effect relationship would not affect the relative ranking of sites.

Radiological health effects in the public are due mainly to radionuclide releases from the repository and subsequent exposure through inhalation or ingestion. The population density within 50 miles of the sites is a key factor in determining the number of radiological fatalities.

Nonradiological worker fatalities at the repository are due to accidents during construction, operation, closure, or decommissioning. In this regard, it is known that mining is a hazardous occupation, even when a great deal of attention is paid to the safety of the workers.

A mechanism by which nonradiological fatalities in the public may result from repository construction and operation is air pollution. However, as seen from Table 4-6 and Appendix F, calculations show that air pollution would not cause any fatalities.

4.3.1.2 Transportation

Transportation assessments are based on the assumption that 70 percent of waste is transported by rail and 30 percent by truck. Although many logistics, economic, and service factors will be involved in the choice between rail and truck transportation more than 10 years hence, the DOE believes this is a reasonable assumption for the purpose of comparing sites. For either mode of transportation, there is a potential for accidents, and small amounts of radiation will be emitted. Both workers and the public will be exposed to any accidents and the released radiation. Estimates of the emitted radiation, the surrounding population densities, the dose-response relationship used for radiological effects from the repository, and the rates of train and truck accidents were used to calculate the base-case estimates of fatalities for the four performance measures characterizing the effects of transportation on health and safety.

The ranges of uncertainty for these four performance measures are due to uncertainty about the analytical models (see Appendix A of the environmental assessments for the nominated sites (DOE, 1986a-e) and Appendix F of this report), the assumptions used in calculating the impacts, and uncertainty about the location of a second repository. In a coordinated waste-management system, a second repository would presumably reduce the cost and risk of waste transportation because the waste could be sent to the nearest repository. The influence of a facility for monitored retrievable storage (MRS) on transportation assessments is not explicitly considered because the MRS facility is not authorized by the Congress at this time.

4.3.2 ENVIRONMENTAL IMPACTS

As mentioned, the environmental impacts were assessed by technical specialists familiar with the environmental assessments for each of the sites. These same people participated in constructing the performance measures.

Concerning the aesthetic impacts, it is necessary to consider potential observation points and sensitive-receptor areas, the location of people visiting or living near a repository, and any natural environmental features of significance. Then judgments must be made about where aesthetic impacts might occur and their significance. A detailed discussion of these judgments is given in Appendix F.

With regard to archaeological, historical, and cultural impacts, the first step is to characterize the number of historical properties of major and minor significance known to be in the vicinity of the nominated sites. Then the likely impact on each is considered as well as the possibilities of mitigating the impact. As a result of this assessment, the base-case impact given current information is specified. The range takes into account the possibilities of discovering additional historical properties at the various sites and of identifying better ways to mitigate potential damage to identified properties.

The appraisal of biological impacts is based on a description in the environmental assessments of the biological resources at the sites and the status of those resources (threatened and endangered, biologically sensitive, or species that are nonunique, nonsensitive, nonendangered, and common throughout the region).

4.3.3 SOCIOECONOMIC IMPACTS

Assessments of socioeconomic impacts are based on a knowledge of the population living in the vicinity of the nominated sites, the characteristics and lifestyles of various segments of that population, and the effects that an influx of money and people may have on those communities. In addition, there may be a disruption of local agriculture, local tourism, or employment opportunities. These are estimated from information in the environmental assessments and from a professional knowledge of what often occurs with a boom-bust cycle in rural communities.

4.3.4 ECONOMIC IMPACTS

Cost estimates for a repository at the various sites were developed by considering separately the costs of siting, construction, operation, and closure and decommissioning. The base-case cost estimates for the Yucca Mountain, Deaf Smith, and Hanford sites are taken from the most recent information (Weston, 1986) developed as part of the DOE's annual evaluation of the adequacy of the fee (1 mill per kilowatt-hour) collected from electric utilities for the Nuclear Waste Fund. For the Davis Canyon and the Richton Dome sites, site-specific cost estimates were prepared for this report. Details of these estimates are given in Appendix F. The ranges for repository costs are plus or minus 35 percent of the base-case estimates. This uncertainty reflects the currently available level of repository-design information (preconceptual stage). Although the DOE is reasonably confident about the ranking of the base-case cost estimates, it recognizes that a first-of-its-kind engineering project like a repository has a high potential for major design changes. These may lead to increases above current estimates.

The base-case estimates of transportation costs were generated with the assistance of a computer model (see Appendix F for details). The range on transportation costs was based on the assumption that a second repository may cause a 40-percent increase or a 46-percent decrease in costs. In addition, it was assumed that a 50-percent increase or decrease in costs should be attributed to uncertainty in the model and the assumptions used to calculate transportation costs.

4.4 THE MULTIATTRIBUTE UTILITY FUNCTION

The selection of sites for characterization would be easy if some sites were more desirable than others on every objective. However, this rarely happens with complex problems, and it did not happen with the five nominated sites. Hence, a key question is, "How much should be given up with regard to one objective to achieve a specified improvement in another?" This key issue is one of value tradeoffs. In addition, because of the uncertainties inherent in the problem, any given site is not guaranteed to yield a specific consequence. At each site there are circumstances that could lead to relatively desirable or undesirable consequences, and the question here is, "Are the potential benefits of having things go right worth the risks of having things go wrong?" This issue concerns attitudes toward risk. Both value tradeoffs and risk attitudes are particularly complicated because there are no right or wrong values. However, the multiattribute utility function can be used to aggregate implications in terms of the individual objectives, using value tradeoffs and attitudes toward risk.

This section presents the multiattribute utility function assessed for evaluating the nominated sites. Details of the assessment procedure are found in Appendix G. The perspective taken was that the sites should be evaluated in terms of minimizing adverse preclosure impacts through specific objectives concerning impacts on health and safety, the environment, socioeconomics, and costs.

The value judgments required to construct the multiattribute utility function were provided by four senior managers (identified in Appendix A) in the DOE's Office of Civilian Radioactive Waste Management, which is responsible for recommending sites for characterization to the Secretary of Energy. The assessment of the multiattribute utility function was done in structured discussions between decision analysts and the DOE managers. This process quantified value judgments about the possible consequences in the problem. The procedure systematically elicited information about value tradeoffs and risk attitudes, and it included many consistency checks. To develop the form of the multiattribute utility function, which is essentially a model of values, one uses value-independence concepts in the same way that probabilistic independence is used in structuring models of impacts. Part of the assessment procedure verified which independence assumptions were appropriate for the objectives used to evaluate the sites.

Given the assumptions verified in Appendix G, an appropriate multiattribute utility function is the additive form*

$$u(x_1,\ldots,x_{14}) = 121 - 1/200 \sum_{i=1}^{14} K_i C_i(x_i), \qquad (4\text{-}1)$$

where the C_i ($i = 1,\ldots,14$) are component disutility functions representing units of the respective performance measures with natural scales and percentage of the range of impacts for the constructed scales, and the K_i ($i = 1,\ldots,14$) are positive scaling factors representing the value tradeoffs between units of the corresponding performance measure and repository costs

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*The more common way of writing the additive utility function u is

$$u(x_1,\ldots,x_{14}) = A + B \sum_{i=1}^{14} k_i u_i(x_i), \qquad (4\text{-}2)$$

where the u_i ($i = 1,\ldots,14$) are the component utility functions scaled from 0 to 1, the k_i ($i = 1,\ldots,14$) are scaling factors that sum to 1, and A and B > 0 are scaling constants chosen to scale u in a manner that facili- tates interpreting the results of the analysis.

As discussed in Appendix G, the k_i factors are difficult to interpret. For this problem, both because preferences decrease with increasing impact levels for all of the performance measures and because the component utility functions are linear for each of the performance measures with natural scales, a more intuitive expression of the utility function for this problem is Equation 4-1. In this expression, the scaling factors K_i ($i = 1,\ldots,14$) are directly interpretable as the assessed value tradeoffs and the C_i ($i = 1,\ldots,14$) are simply the units of impact. With Equation 4-2, the k_i and the u_i are derived from the value tradeoffs and the scaling convention for the problem. Since preferences decrease with increasing impact levels, the minus sign in front of the 1/200 term in Equation 4-1 is needed and the C_i can be interpreted as disutility functions.

measured in millions of dollars. The specific C_i and K_i values that were assessed are given in Table 4-7.

The factors 121 and -1/200 in Equation 4-1 are necessary to scale the utility from 0 to 100, where 100 is chosen to represent a particularly desirable set of impacts for all performance measures and 0 represents a particularly undesirable set of impacts for all performance measures. For this purpose, the ranges of the performance measures listed in Table 4-7 were chosen to be broad enough to include all possible impacts for the sites being evaluated. The utilities of 0 and 100 are assigned by Equation 4-1 to the sets of impacts represented by the highest levels and the lowest levels in Table 4-7, respectively. Because the utility function is additive and because the component utility function for repository cost is linear, it is particularly easy to interpret units, referred to as "utiles," of the multiattribute utility function (Equation 4-1) in terms of equivalent costs. Specifically, one utile is equivalent in value to 200 million dollars.

To get an intuitive feeling for the C_i and the K_i terms in Equation 4-1, some examples are helpful. The component disutility function C_i for worker cancer fatalities from the repository is simply x_1, which represents the number of such fatalities. For aesthetic impacts, the component disutility function C_9 represents the percentage of the highest level of aesthetic impact described in Table 4-2. The highest level is level 6, so $C_9(6) = 100$. Since $C_9(4) = 33$, as shown in Table 4-7, aesthetic impacts of level 4 are assessed as being one-third as detrimental as impacts of level 6 (i.e., 33 is one-third of 100).

The value tradeoff K_8 is 4, which means that the impact of one statistical public fatality due to a transportation accident is deemed as undesirable as an additional cost of 4 million dollars. The value tradeoff $K_9 = 1$ means that the impact of an additional 1 percent of aesthetic degradation is deemed as undesirable as an additional cost of 1 million dollars. The value tradeoff $K_{14} = 1$ means that a million dollars in transportation cost is deemed equivalent to a million dollars in repository cost. That $K_{13} = 1$ is by definition.

The multiattribute utility function assessed in this problem can be interpreted as follows. In situations where there is uncertainty about the impacts, the expected (i.e., average) utility can be used to appraise the relative desirability of consequences (i.e., set of impact levels). Higher expected utilities indicate preferred alternatives. In addition, the assessment described in Appendix G indicates that the multiattribute utility function is also a measurable-value function. Hence, differences in utility have a useful interpretation. Namely, the relative differences in desirability between two consequences can be measured by the differences in utility between those consequences. Furthermore, the relative differences in desirability between two alternatives can be measured by the differences in expected utilities between those alternatives.

To calculate the utility of a consequence with the utility function (Equation 4-1), clearly the only variable term is

$$C(x_1,\ldots,x_{14}) = \sum_{i=1}^{14} K_i C_i(x_i), \qquad (4\text{-}3)$$

Table 4-7. Parameters in the base-case multiattribute utility function and equivalent-consequence function

Performance measure	Impact range: Lowest level	Impact range: Highest level	Utility-function components: Value tradeoff K	Utility-function components: Component disutility function C
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 4-2)	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, etc., impacts (see Table 4-3)	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 4-4)	0	5	0.3	$C_{11}(0)=0$, $C_{11}(1)=4$, $C_{11}(2)=10$, $C_{11}(3)=18$, $C_{11}(4)=40$, $C_{11}(5)=100$
X_{12} = socioeconomic impacts (see Table 4-5)	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)	4000	19,000	1	x_{13}
X_{14} = transportation cost (millions of dollars)	200	4200	1	x_{14}

which can be thought of as an equivalent-consequence function. With this function, higher numbers represent more-severe consequences and are less preferred. Because the multiattribute utility function is additive and the utility function for cost is linear, each unit of the equivalent consequence calculated with Equation 4-3 can be taken to be as undesirable as an additional cost of 1 million dollars.

4.5 EVALUATION OF THE NOMINATED SITES

The impacts of the five sites in terms of the performance measures are combined with the value judgments expressed in the multiattribute utility function to provide an overall evaluation of the desirability of the sites. The first part of this section presents aggregations of informative performance-measure categories. The complete base-case analysis follows in the second part. Numerous sensitivity analyses involving changes in the possible impacts and also changes in the multiattribute utility function for evaluating these impacts are presented in Section 4.6.

4.5.1 BASE-CASE ANALYSIS

Table 4-8 uses the component disutility functions in Table 4-7 to convert the base-case estimates of impacts for each site to component disutilities. These can be easily substituted into the utility function (Equation 4-1) or the equivalent-consequence function (Equation 4-3) to evaluate the sites. The component disutilities are identical with the base-case estimates of impacts in Table 4-6 except for the environmental and socioeconomic performance measures. To calculate the equivalent consequence for a site, Equation 4-3 is used. For each site, the appropriate K_i value from Table 4-7 is multiplied by the appropriate C_i value from Table 4-8 to obtain the equivalent-consequence impacts for each performance measure in Table 4-9. Before examining these results for all five sites, let us look at the calculations for the Richton Dome site.

In Table 4-8, the number of nonradiological public fatalities from transportation to Richton Dome, represented by performance measure X_8, is 5.3. In Table 4-7, the value tradeoff K_8 between units of this performance measure and costs is 4, indicating that 4 million dollars in additional cost is indifferent to a statistical nonradiological public fatality from transportation. Hence, the 5.3 fatalities is multiplied by the 4 million dollars per fatality to yield a 21.2 contribution to the equivalent-consequence impact associated with performance measure X_8 for the Richton Dome site (Table 4-9). Regarding socioeconomic impacts (X_{12}), impact level 2 in Table 4-5 describes that impact at Richton Dome. This has a disutility of 20, as shown in Table 4-8. The value tradeoff K_{12} for a unit (i.e., percent) of socioeconomic impacts is 5 million dollars, as indicated in Table 4-7. Multiplying 20 by 5 yields the contribution of 100 to the equivalent-consequence impact for performance measure X_{12} in Table 4-9. The rest of the entries in Table 4-9 in the column for the Richton Dome site can be calculated similarly.

Table 4-8. Base-case component disutilities of nominated sites[a]

	Performance measure	Richton Dome	Deaf Smith	Davis Canyon	Yucca Mt.	Hanford
X_1 =	repository-worker radiological fatalities	2	2	2	4	9
X_2 =	public radiological fatalities from repository	0.7	0.5	0.1	0.1	0.7
X_3 =	repository-worker non-radiological fatalities	27	29	27	18	43
X_4 =	public nonradiological fatalities from repository	0	0	0	0	0
X_5 =	transportation-worker radiological fatalities	0.52	0.64	0.73	0.81	0.90
X_6 =	public radiological fatalities from transportation	2.4	2.9	3.5	4.1	4.3
X_7 =	transportation-worker nonradiological fatalities	1.3	1.6	2.1	2.5	2.7
X_8 =	public nonradiological fatalities from transportation	5.3	6.7	8.4	10.2	11
X_9 =	aesthetic impacts	33	33	100	33	3
X_{10} =	archaeological, historical, and cultural impacts	6	12	56	23	6
X_{11} =	biological impacts	15	12	29	10	12
X_{12} =	socioeconomic impacts	20	16	20	6	3
X_{13} =	repository cost	9000	9500	10,400	7500	12,900
X_{14} =	transportation cost	970	1120	1240	1400	1450

[a]Component disutilities are calculated by substituting the base-case estimates of impacts shown in Table 4-6 into the component disutility function in Table 4-7.

Table 4-10 aggregates the information in Table 4-9 in numerous ways to gain insights into the comparative advantages and disadvantages of the sites in informative performance-measure categories. Row 1 of Table 4-10 shows that the relative ranking of the nominated sites on preclosure radiological safety is Richton Dome, Deaf Smith, Davis Canyon, Yucca Mountain, and Hanford. The difference between the first-ranked site and the fifth-ranked site is equivalent to 15 million dollars, a difference largely attributable to waste transportation.

Row 2 of Table 4-10 shows that the relative ranking of sites on worker fatalities (radiological and nonradiological) is Yucca Mountain, Richton Dome, Davis Canyon, Deaf Smith, and Hanford. The Yucca Mountain site is slightly

Table 4-9. Base-case equivalent-consequence impacts[a]

Performance measure	Richton Dome	Deaf Smith	Davis Canyon	Yucca Mt.	Hanford
X_1 = repository-worker radiological fatalities	2	2	2	4	9
X_2 = public radiological fatalities from repository	2.8	2	0.4	0.4	2.8
X_3 = repository-worker non-radiological fatalities	27	29	27	18	43
X_4 = public nonradiological fatalities from repository	0	0	0	0	0
X_5 = transportation-worker radiological fatalities	0.52	0.64	0.73	0.81	0.90
X_6 = public radiological fatalities from transportation	9.6	11.6	14	16.4	17.2
X_7 = transportation-worker nonradiological fatalities	1.3	1.6	2.1	2.5	2.7
X_8 = public nonradiological fatalities from transportation	21.2	26.8	33.6	40.8	44
X_9 = aesthetic impacts	33	33	100	33	3
X_{10} = archaeological, historical, and cultural impacts	1.2	2.4	11.2	4.6	1.2
X_{11} = biological impacts	4.5	3.6	8.7	3.0	3.6
X_{12} = socioeconomic impacts	100	80	100	30	15
X_{13} = repository cost	9000	9500	10,400	7500	12,900
X_{14} = transportation cost	970	1120	1240	1400	1450

[a] Equivalent-consequence impacts in million of dollars are computed by multiplying the base-case component disutilities shown in Table 4-8 by the value tradeoffs shown in Table 4-7.

preferred to the three salt sites, which are barely distinguishable from one another, while the Hanford site is notably less favorable. This marked difference is attributable to nonradiological fatalities in repository workers (mostly from mining accidents), which, in turn, reflects the larger labor requirements for repository construction and operation at the Hanford site.

Row 3 of Table 4-10 aggregates the health-and-safety impacts on the public. The relative ranking is Richton Dome, Deaf Smith, Davis Canyon, Yucca Mountain, and Hanford. The differences between the sites range from the equivalent of 6 to 30 million dollars and are largely attributable to waste transportation.

Table 4-10. Base-case equivalent-consequence impacts for various aggregations of performance measures[a]

Row	Performance-measure category[b]	Richton Dome	Deaf Smith	Davis Canyon	Yucca Mountain	Hanford
1	Radiological fatalities (X_1, X_2, X_5, X_6)	15	16	17	22	30
2	Worker fatalities (X_1, X_3, X_5, X_7)	31	33	32	25	56
3	Public fatalities (X_2, X_4, X_6, X_8)	34	40	48	58	64
4	Health and safety (X_1 through X_8)	64	74	80	83	120
5	Environment and socioeconomics (X_9 through X_{12})	139	119	220	71	23
6	Public near site (X_2, X_4, X_9 through X_{12})	142	121	220	71	26
7	Site impacts (X_1 through X_4, X_9 through X_{12})	171	152	249	93	78
8	Noncosts (X_1 through X_{12})	203	193	300	154	142
9	Noncosts and transportation costs (X_1 through X_{12}, X_{14})	1,173	1,313	1,540	1554	1,592
10	Noncosts and repository costs (X_1 through X_{12}, X_{13})	9,203	9,693	10,700	7654	13,042
11	Total equivalent impact (X_1 through X_{14})	10,173	10,813	11,940	9054	14,492

[a]The numbers in this table represent the equivalent-consequence impacts in millions of dollars rounded to the nearest unit. The numbers for certain categories (e.g., row 4) do not add because of rounding off.

[b]See Table 4-1 for definitions of the performance measures X_1 through X_{14}.

Row 4 of Table 4-10 shows that the relative ranking of sites against all health-and-safety impacts is Richton Dome, Deaf Smith, Davis Canyon, Yucca Mountain, and Hanford. In terms of equivalent-consequence impacts, the difference between the sites ranked first and fourth (equivalent to 19 million dollars) is about half the difference between the sites ranked fourth and fifth (equivalent to 37 million dollars).

Row 5 of Table 4-10 shows that the relative ranking of sites on all of the environmental and socioeconomics performance measures is Hanford, Yucca Mountain, Deaf Smith, Richton Dome, and Davis Canyon. The difference between the sites ranked fourth and fifth, Richton Dome and Davis Canyon, respectively, is most significant, equivalent to 81 million dollars (about 70 percent of the difference between the sites ranked first and fourth).

Row 6 of Table 4-10 aggregates the impacts that might be considered as adverse impacts on the public living near a site. It shows that the relative ranking of sites is Hanford, Yucca Mountain, Deaf Smith, Richton Dome, and

Davis Canyon--the same ranking as that obtained by considering only environmental and socioeconomic impacts. The most significant difference is between the sites ranked fourth and fifth--that is, Richton Dome and Davis Canyon. Row 7 of Table 4-10 includes the health-and-safety impacts on the workers at the repository and hence might be considered an aggregation of the total impact felt by all members of the community near a site. The ranking remains Hanford, Yucca Mountain, Deaf Smith, Richton Dome, and Davis Canyon.

If all noncost performance measures are aggregated, as in row 8 of Table 4-10, the relative ranking is Hanford, Yucca Mountain, Deaf Smith, Richton Dome, and Davis Canyon. Again, the most significant difference is between the sites ranked fourth and fifth; this difference is equivalent in value to 97 million dollars. This difference is larger than that between the sites ranked first and fourth (equivalent to 61 million dollars). This ranking is changed drastically by the addition of costs. When transportation costs are combined with the noncost performance measures, the ranking becomes Richton Dome, Deaf Smith, Davis Canyon, Yucca Mountain, and Hanford (row 9, Table 4-10). When repository costs are combined with the noncost performance measures, the ranking becomes Yucca Mountain, Richton Dome, Deaf Smith, Davis Canyon, and Hanford (row 10, Table 4-10). When both transportation and repository costs are combined with the noncost performance measures (i.e., all performance measures are considered), the ranking is Yucca Mountain, Richton Dome, Deaf Smith, Davis Canyon, and Hanford (row 11, Table 4-10).

4.6 SENSITIVITY ANALYSES

Many sensitivity analyses can be conducted to determine which of the impacts and value judgments are critical to any implications drawn from the analysis. This section presents several sensitivity analyses to determine the main factors that may influence these implications. In most cases the sensitivity analyses examine the effects of changing impact levels and value judgments on the total equivalent-consequence impacts (row 11, Table 4-10). The first set of sensitivity analyses focuses on changes in the impacts from the base case described in Table 4-6. The second set of sensitivity analyses examines changes in the multiattribute utility function for evaluating impacts.

4.6.1 SENSITIVITY ANALYSES INVOLVING IMPACTS

Given the base-case impacts and the elicited value judgments about them, the implications of the analysis seem most likely to be affected by changes in socioeconomic impacts, transportation-related impacts, and repository cost. Each of these, as well as other situations, are considered below. These sensitivity analyses examine the significance of uncertainties about preclosure impacts to the relative desirability of sites. The insensitivity of the implications of the analysis to the level of impact within the specified ranges of Table 4-6 is the main justification for the degree to which preclosure uncertainties are examined in the analysis.

4.6.1.1 Socioeconomic impacts

In one sensitivity analysis, the socioeconomic impacts in Table 4-6 were changed from the base-case estimate to the high estimate and then to the low estimate. Thus, for example, for the high estimate, the socioeconomic impact of the Deaf Smith site was specified as level 3 rather than the base-case level 1.67, and the impact of the Yucca Mountain site was specified as level 2 rather than the base-case level 0.67. The equivalent-consequence impacts of the five sites for these cases are shown in Table 4-11. Yucca Mountain remains the most favorable site, the salt sites still maintain the same order as in the base case, and Hanford is still the least favorable site for both changes. Indeed, if the socioeconomic impacts for any site are set at the low level while for all other sites they are set at the high level, there is no change in the overall ranking of sites.

Table 4-11. Sensitivity of total equivalent-consequence impacts to socioeconomic impacts[a]

Socioeconomic impact level	Richton Dome	Deaf Smith	Davis Canyon	Yucca Mt.	Hanford
Low level	10,113	10,773	11,900	9039	14,477
Base case	10,173	10,813	11,940	9054	14,492
High level	10,373	11,033	12,140	9124	14,507

[a]The numbers in this table represent the total equivalent-consequence impacts in million of dollars, with socioeconomic impact levels as indicated and all other performance measures at the base-case level.

4.6.1.2 Low transportation impacts

Because of the uncertainty about the second geologic repository, it seemed prudent to examine the implications of a low-transportation-impact scenario. The performance measures related to transportation are X_5 through X_8 and X_{14}. When all impacts for these performance measures are set at the low level of their ranges in Table 4-6, the equivalent-consequence evaluations shown in row 1 of Table 4-12 result. Again, the salt sites maintain the ranking Richton Dome, Deaf Smith, and Davis Canyon. Yucca Mountain is preferred to Richton Dome by the equivalent of 1448 million dollars, and Deaf Smith is preferred to Hanford by 3424 million dollars.

If in addition to the low transportation impacts the socioeconomic impacts are moved to the high (i.e., least desirable) level, the equivalent-consequence impacts in row 2 of Table 4-12 result. Again, Yucca Mountain is the preferred site, and the ranking of the salt sites is maintained. The Hanford site is still a distant fifth. If for the low-transportation-impacts

Table 4-12. Sensitivity of the total equivalent-consequence impacts to transportation impacts and varied socioeconomic impacts[a]

Row	Impact level[b]	Richton Dome	Deaf Smith	Davis Canyon	Yucca Mt.	Hanford
1	X_5 through X_8 and X_{14} low level, X_{12} base-case level	9,441	9,965	10,996	7993	13,389
2	X_5 through X_8 and X_{14} low level, X_{12} high level	9,641	10,185	11,196	8063	13,404
3	X_5 through X_8 and X_{14} low level, X_{12} low level	9,381	9,925	10,956	7978	13,374
4	Base case	10,173	10,813	11,940	9054	14,492

[a]The numbers in this table represent the total equivalent-consequence impacts in millions of dollars of all performance measures at their base-case levels except those indicated in the "impact level" column.

[b]Table 4-1 for definitions of the performance measures X_5, X_8, etc.

scenario the socioeconomic impacts are placed at their low level, the equivalent-consequence impacts that result are shown in row 3 of Table 4-12. These results are identical with those obtained when the socioeconomic impacts are placed at their base-case levels for the low-transportation-impact scenario.

4.6.1.3 Repository costs

Because the repository costs have such a wide range in uncertainty (i.e., in the billions of dollars), they have a significant effect on the equivalent-consequence impacts. This does not necessarily imply, however, that this uncertainty has a significant effect on the relative ranking of the sites or the implications of the analysis for selecting three sites for characterization. Table 4-13 illustrates this.

Table 4-13. Sensitivity of the total equivalent-consequence impacts to repository costs[a]

Repository-cost impact level	Richton Dome	Deaf Smith	Davis Canyon	Yucca Mt.	Hanford
Low level	7,023	7,488	8,300	6,429	9,977
Base-case level	10,173	10,813	11,940	9,054	14,492
High level	13,323	14,138	15,580	11,679	19,007

[a]The numbers in the table represent the total equivalent-consequence impacts in millions of dollars of all performance measures at their base-case level except for repository cost, which is at the level indicated.

If the repository cost for each site is set at the low level, the equivalent consequence of each site decreases from the base case. The ranking of the sites does not change, though the specific differences in equivalent-consequences among the sites are narrowed. The differences are, however, still very significant. If the repository cost for each of the sites is set at its high level, the equivalent-consequence implications are again identical with those for the base case.

Even when their repository costs are at the high levels, Yucca Mountain, Richton Dome, and Deaf Smith are still more favorable than Hanford with the repository cost at the base-case level. On the other hand, if the cost of the Hanford site is at its low level and the costs for the other sites are at the base-case levels, Hanford is slightly preferred to Richton Dome but less preferred than Yucca Mountain. In general, however, one expects a positive correlation between the costs of constructing a repository at any of the sites. Thus this scenario appears very unlikely.

4.6.1.4 Ranges of other noncost performance measures

If all of their noncost performance measures are moved to the high levels of their ranges in Table 4-6, the Richton Dome and the Deaf Smith sites would still be preferred to the Davis Canyon site even if its noncost impacts are assumed to be low. If all of the noncost performance measures are at their high levels for Richton Dome and all of these performance measures are at their low levels for Deaf Smith, Richton Dome is still preferable to Deaf Smith. Similarly, even if all of the noncost impacts of Yucca Mountain are set at their high levels and all of the noncost impacts of the Hanford site are set at their low levels, the Yucca Mountain site would still be more favorable than the Hanford site. The results of several sensitivity analyses are shown in Table 4-14.

Table 4-14. Sensitivity analysis of performance measures other than repository cost[a]

Impact level[b]	Richton Dome	Deaf Smith	Davis Canyon	Yucca Mt.	Hanford
High except X_{13} and X_{14} at base case	10,445	11,111	12,200	9,211	14,588
Low except X_{13} and X_{14} at base case	10,045	10,704	11,847	8,957	14,407
High except X_{13} at base case	11,515	12,341	13,560	10,751	16,178
Low except X_{13} at base case	9,335	9,884	10,937	7,937	13,347

[a]The numbers in this table represent the total equivalent-consequence impacts in millions of dollars of performance measures set at the levels indicated.
[b]X_{13} and X_{14} are repository cost and waste-transportation cost, respectively.

4.6.2 SENSITIVITY ANALYSES INVOLVING VALUE JUDGMENTS

The sensitivity analyses described below investigated the implications of different value tradeoffs between key performance measures, possible risk-averse and risk-prone attitudes, and the form of the overall multiattribute utility function.

4.6.2.1 Value tradeoffs among statistical fatalities

As shown in Table 4-7, the base-case value tradeoff for worker fatalities was that an additional cost of 1 million dollars is equivalent to one statistical worker fatality; for public fatalities the value tradeoff is an additional cost of 4 million dollars for one statistical public fatality. Furthermore, the base case assumed that these tradeoffs were identical for both radiological and nonradiological fatalities. Four variations of these base-case value tradeoffs were considered in the sensitivity analyses. The first two sensitivity analyses varied the value tradeoff for a public fatality versus a worker fatality from a ratio of 1:1 to 20:1, implying that the statistical fatality of a member of the public was equivalent to an additional cost of 1 million dollars in the first case and 20 million dollars in the second case. The next two sensitivity analyses varied the relative value on radiological and nonradiological fatalities from a ratio of 3:1 to 1:3.

Table 4-15 shows the results in terms of the equivalent-consequence evaluations for the four cases, as well as the base case repeated from Table 4-10. The results show almost the same relative ranking in all situations (although the spread between sites changes) except for the case where a worker fatality and a public fatality are valued equally. In this case the Yucca Mountain site is slightly more favorable than the Davis Canyon and the Deaf Smith sites, whereas the reverse holds in the base case. These differences, however, have no effect at all on the overall rankings of the sites.

4.6.2.2 Value tradeoffs between statistical fatalities and costs

Because of the importance to everyone of the value tradeoffs between statistical fatalities and costs, it is prudent to examine the implications of a wide range of these value tradeoffs. The base-case value tradeoffs were increased by factors of 5 and 25 in two sensitivity analyses. In the former case, the value tradeoffs for statistical public and worker fatalities were set at 20 and 5 million dollars, respectively. In the latter case, these value tradeoffs were 100 and 25 million dollars, respectively. The equivalent-consequence implications for health-and-safety impacts are presented, along with the base case, in Table 4-16. The implications of these changes are identical with those of the base case. In all cases, the overall site rankings are Yucca Mountain, Richton Dome, Deaf Smith, Davis Canyon, and Hanford.

Table 4-15. Sensitivity analysis of value tradeoffs among statistical fatalities

Variation from base case	Value tradeoff (millions of dollars per fatality) Worker radiological (K_1,K_5)	Worker nonradiological (K_2,K_6)	Public radiological (K_3,K_7)	Public nonradiological (K_4,K_8)	Site[A] Richton Dome	Deaf Smith	Davis Canyon	Yucca Mountain	Hanford
None (i.e., base case)	1	1	4	4	64	74	80	83	120
1 public fatality = 1 worker fatality	1	1	1	1	39	43	44	40	72
1 public fatality = 20 worker fatalities	1	1	20	20	199	235	272	313	376
1 radiological fatality = 3 nonradiological fatalities	3	1	12	4	94	106	114	126	179
1 nonradiological fatality = 3 radiological fatalities	1	3	4	12	163	188	205	206	299

[A] The numbers in these columns represent equivalent-consequence impacts in millions of dollars for the base-case health-and-safety impacts, given the value tradeoffs stated in the table.

Table 4-16. Sensitivity analysis of value tradeoffs between statistical fatalities and costs

Variation from base case	Value tradeoff (millions of dollars per fatality)		Site[A]				
	Worker (K_1,K_3,K_5,K_7)	Public (K_2,K_4,K_6,K_8)	Richton Dome	Deaf Smith	Davis Canyon	Yucca Mountain	Hanford
Base case	1	4	64	74	80	83	120
5 times base case	5	20	320	370	400	415	600
25 times base case	25	100	1600	1850	2000	2075	3000

[A] The numbers in these columns represent equivalent-consequence impacts in millions of dollars for the base-case health-and-safety impacts, given the value tradeoffs stated in the table.

4.6.2.3 Value tradeoffs between socioeconomic impacts and costs

The base-case value tradeoff between costs and socioeconomic impacts is that to reduce the maximum level of socioeconomic impacts to zero is equivalent to 500 million dollars. If this value tradeoff is doubled to 1000 million dollars, the equivalent-consequence evaluations in Table 4-17 result. There is no change in the relative ranking of the sites.

The multiattribute utility function can be changed simultaneously with changes in possible impacts. The low-transportation-impact scenario (Section 4.6.1.2), which assumes that the impacts on performance measures X_5 through X_8 and X_{14} are at their lowest level as well as a value tradeoff of 1000 million dollars for socioeconomics, the equivalent-consequence evaluations in the last row of Table 4-17 result. Here again, the relative ranking of the sites remains the same.

Table 4-17. Sensitivity analysis of value tradeoffs for socioeconomic impacts[a]

Variation from base case	Richton Dome	Deaf Smith	Davis Canyon	Yucca Mt.	Hanford
Base case ($K_{12} = 5$)	10,173	10,813	11,940	9054	14,492
Double socioeconomic value tradeoff so $K_{12} = 10$	10,273	10,893	12,040	9084	14,507
Low transportation impacts with $K_{12} = 10$	9,541	10,045	11,096	8023	13,404

[a] The numbers in this table represent the total equivalent-consequence impacts in millions of dollars for the base-case ratings and values except as noted in the first column.

4.6.2.4 Sensitivity to risk attitudes about fatalities

To examine the implications of risk attitudes about fatalities, note from the multiattribute utility function (Equation 4-1) and the information in Table 4-7 that an aggregate health-and-safety consequence function C_H is

$$C_H(x_1,\ldots,x_8) = x_1 + x_3 = x_5 + x_7 + 4(x_2 + x_4 + x_6 + x_8), \qquad (4\text{-}4)$$

where C_H is measured in equivalent-consequence impacts, which in this case can also be interpreted as equivalent worker fatalities. Using the ranges from Table 4-6, this function is linearly scaled from the lowest level of no equivalent worker fatalities to 350 equivalent worker fatalities for the highest level. Using the linear fatality function, a lottery that yields a 50-50 chance at no fatalities and a 50-50 chance at 350 fatalities is indifferent to 175 fatalities, which is the expected number of fatalities for the lottery. This is referred to as a risk-neutral attitude.

The risk-averse attitude considered here is when this same lottery is indifferent to 250 fatalities for sure, which is significantly greater than the expected number of fatalities. Since the utility function has been shown to also be a measurable-value function, this risk-averse attitude implies that the relative importance of the first 250 equivalent worker fatalities is exactly equal to the relative importance of the next 100 worker fatalities. In addition, this risk aversion is equivalent to a marginally increasing disutility, meaning that the change from one to two statistical fatalities is more significant than the change from zero to one, and so on.

The risk-prone attitude toward health effects is when a lottery yielding a 50-50 chance at each of 0 or 350 equivalent worker fatalities is indifferent to 100 worker fatalities for sure, much less than the expected number of fatalities. In this case, the relative importance of the first 100 equivalent worker fatalities is equal to that of the next 250 worker fatalities.

Assuming exponential consequence functions fit to the risk-averse and the risk-prone cases and that the change from zero to one statistical worker fatality is as undesirable as an increase of 1 million dollars in cost (i.e., the base-case linear value tradeoff), the aggregate consequence functions for fatalities are

$$C_H(x_1,\ldots,x_8) = -177 + 1271 \exp[0.00563(c_H-350)] \qquad (4\text{-}5)$$

and

$$C_H(x_1,\ldots,x_8) = 178 - 24.83 \exp[0.00563(350-c_H)], \qquad (4\text{-}6)$$

where C_H is the equivalent-consequence impact and c_H is the number of equivalent worker fatalities. As shown in Table 4-18, the relative rankings of the sites do not change with either of these risk attitudes.

Table 4-18. Sensitivity to risk attitudes about fatalities[a]

Variation from base case	Richton Dome	Deaf Smith	Davis Canyon	Yucca Mt.	Hanford
Base case (risk neutral)	10,173	10,813	11,940	9054	14,492
Risk averse for fatalities	10,186	10,831	11,961	9077	14,543
Risk prone for fatalities	10,163	10,800	11,925	9038	14,459

[a] The numbers in this table represent the total cost-equivalent impacts in millions of dollars for the base-case ratings, with risk attitudes changed as noted in the first column.

4.6.3 SENSITIVITY ANALYSIS OF THE FORM OF THE UTILITY FUNCTION

It seems useful to analyze whether changing the overall evaluation model to account for a general risk attitude could change the implications of the analysis. To analyze this possibility, one can treat the utility function (Equation 4-1) as a measurable-value function only and place either a risk-averse or a risk-prone attitude on the resulting measurable values. As indicated in Appendix G, a new utility function U for this case can be written

$$U(x_1,\ldots,x_{14}) = A + B \exp[cu(x_1,\ldots,x_{14})], \qquad (4\text{-}7)$$

where A and B are constants to ensure that U has the same range as u from 0 to 100 and c is a constant indicating the risk attitude. If c is positive, then the attitude is risk prone; if c is negative, a risk-averse attitude is implied. Also, for this sensitivity analysis, it is assumed that there are significant uncertainties in the problem. Specifically, it is assumed that the uncertainty about the impacts of each site can be summarized by a probability distribution yielding either all high estimates or all low estimates from Table 4-6 with a probability of .2 for each. For all base-case estimates from Table 4-6 the probability is assumed to be .6. Equivalent consequences for these situations are shown in Table 4-19.

Table 4-19. Equivalent-consequence impacts of the high-impact, low-impact, and base-case estimates[a]

Impact level	Richton Dome	Deaf Smith	Davis Canyon	Yucca Mt.	Hanford
High impacts	14,665	15,666	17,200	13,376	20,693
Base case	10,173	10,813	11,940	9,054	14,492
Low impacts	6,185	6,559	7,297	5,312	8,832

[a]The numbers in this table represent the total equivalent-consequence impacts in millions of dollars for performance measures set at the levels indicated.

The results are shown in Table 4-20. In row 1, the equivalent consequences are shown for the base-case analysis. Rows 2 and 3 show the results of the risk-averse situation where there is a penalty on being rated particularly unfavorably on several performance categories simultaneously. For both of these situations, the overall evaluation of the sites remains identical with that in the base case. In rows 4 and 5, risk proneness is considered. Here, there is a willingness to take a chance in order to get all of the performance-measure categories at better levels simultaneously. In these cases, the relative rankings of the sites also remain the same.

Table 4-20. Sensitivity analysis of the overall risk attitude[a]

Variation from base case[b]	Richton Dome	Deaf Smith	Davis Canyon	Yucca Mt.	Hanford
Base case with uncertainty (additive)	10,270	10,940	12,060	9170	14,600
Multiattribute risk aversion	10,400	11,090	12,240	9288	14,850
Strong multiattribute risk aversion	10,620	11,340	12,540	9488	15,280
Multiattribute risk proneness	10,150	10,790	11,890	9054	14,350
Strong multiattribute proneness	9,933	10,550	11,600	8862	13,940

[a]The numbers in this table represent the total equivalent-consequence impacts in millions of dollars for the base-case estimates, with multiattribute risk attitudes changed as noted.

[b]The utility functions of the form in Equation 4-7 were chosen to be consistent with risk attitudes determined by specifying the certainty equivalent (CE) for a lottery corresponding to an equivalent-consequence impact of 5000 with a probability of .5 and an equivalent-consequence impact of 20,000 with a probability of .5. Thus, for instance, the certainty equivalent for the strong-risk-aversion case is that 15,000 is indifferent to an 50-50 chance at each of 5000 and 20,000. For the base-case linear utility function in Equation 4-1, the certainty equivalent for the lottery is 12,500. The certainty equivalents and the utility functions for the five cases are as follows:

Case	CE	Utility function
Base case	12,500	$U = u$
Risk aversion	13,500	$U = 195\ [1 - \exp(-0.00719u)]$
Strong risk aversion	15,000	$U = 117\ [1 - \exp(-0.0193u)]$
Risk proneness	11,500	$U = 95.1\ [\exp(0.00719u - 1)]$
Strong risk proneness	10,000	$U = 17.1\ [\exp(0.0193u - 1)]$

4.6.4 OTHER SENSITIVITY ANALYSES OF THE SET OF OBJECTIVES

Sections 4.1 and 4.2 presented the basis for selecting the objectives and associated performance measures used in this analysis. As explained in Appendix G, other potential objectives were not included because it was felt that their inclusion would not affect the implications of the analysis. Some objectives concerned nonfatal health-and-safety effects (e.g., illness and injuries), and another objective concerned the socioeconomic impacts of the transportation system. The possible implications of including these objectives in the analysis are now considered with a knowledge of the study results.

Nonfatal health-and-safety effects are likely to be highly correlated with the fatalities. Their inclusion would therefore have implications similar to those from a greater value being placed on fatalities. Thus, as illustrated in Table 4-16, the inclusion of nonfatal health-and-safety effects should not affect the implications of the analyses.

The socioeconomic impacts of waste transportation are probably directly related to the total number of miles traveled to deliver waste to the repository and hence to the transportation impacts. These impacts, represented by performance measures X_5 through X_8 and X_{14}, have the same ranking as the overall impacts for the salt sites and Hanford. The socioeconomic impacts of waste transportation to Yucca Mountain could be slightly greater than those associated with the salt sites. Given the overall differences in desirability indicated by the equivalent-consequence impacts in row 11 of Table 4-10, it is unlikely that there would be any change in the ranking of the sites.

4.7 CONCLUSIONS FROM THE PRECLOSURE ANALYSIS

This section summarizes the conclusions for the overall base-case analysis and the sensitivity analyses. Before discussing the overall preclosure analysis, it is useful to review the conclusions with regard to informative performance-measure categories.

Table 4-21 shows the equivalent-consequence impacts and rankings of sites on the performance-measure categories of health and safety, environment and socioeconomics, noncosts, and costs. The ranking on health-and-safety impacts is Richton Dome, Deaf Smith, Davis Canyon, Yucca Mountain, and Hanford. In terms of equivalent-consequence impacts, the difference between the sites ranked first and fourth is about half the difference between the sites ranked fourth and fifth. The differences in the rankings on health and safety are largely attributable to nonradiological repository-worker fatalities due to accidents and to waste-transportation impacts (radiological and nonradiological) on the public, and to the importance associated with each type of impact (reflected by the value tradeoffs).

Table 4-21. Summary of base-case analysis[a]

Site	Health and safety	Environment and socioeconomics	Noncosts	Costs	Overall equivalent impacts	Base-case utility[b]
Yucca Mountain	83 (4)	71 (2)	154 (2)	8,900 (1)	9,054 (1)	75.7 (1)
Richton Dome	64 (1)	139 (4)	203 (4)	9,970 (2)	10,173 (2)	70.1 (2)
Deaf Smith	74 (2)	119 (3)	193 (3)	10,620 (3)	10,813 (3)	66.9 (3)
Davis Canyon	80 (3)	220 (5)	300 (5)	11,640 (4)	11,940 (4)	61.3 (4)
Hanford	120 (5)	23 (1)	142 (1)	14,350 (5)	14,492 (5)	48.5 (5)

[a] The numbers in the first five columns represent equivalent-consequence impacts in millions of dollars. The numbers in parentheses represent the ranking of the sites.

[b] Calculated for each site with Equation 4-1. In interpreting differences in base-case utility, the reader should recall that one utile is equal in value to 200 million dollars.

The ranking of sites on the aggregate of environmental and socioeconomic performance measures is Hanford, Yucca Mountain, Deaf Smith, Richton Dome, and Davis Canyon. Hanford and Yucca Mountain are most preferable in this category because they have the lowest levels of impact in the component performance measures (i.e., environment and socioeconomics). Deaf Smith has moderate levels of impact in both performance measures and is ranked third. Richton Dome is ranked fourth, mostly because of socioeconomic impacts. Davis Canyon is ranked fifth because it has the highest levels of impact in both performance measures; it is significantly less preferred in the environmental category.

The third column in Table 4-21, labeled "noncosts," aggregates the health-and-safety impacts and the environmental and socioeconomic impacts discussed above. The ranking is Hanford, Yucca Mountain, Deaf Smith, Richton Dome, and Davis Canyon. It is clear from this ranking that the differences among the sites with regard to health-and-safety impacts are overwhelmed by the differences with regard to the environment and socioeconomics (compare differences in equivalent-consequence impacts in the second and third columns).

The fourth column in Table 4-21 shows the ranking of the sites obtained by combining repository costs and transportation costs. From Table 4-9 (last two rows), it is clear that repository costs dominate the ranking in this performance-measure category.

With these rankings on performance-measure categories in mind, the conclusions for the overall base-case analysis and the sensitivity analyses can be summarized.

The overall equivalent-consequence impacts and ranking of sites for the preclosure period are shown in the fifth column in Table 4-21. The overall preclosure ranking is Yucca Mountain, Richton Dome, Deaf Smith, Davis Canyon, and Hanford. In terms of equivalent-consequence impacts, the difference between Yucca Mountain and Richton is the equivalent of 1119 million dollars, between Richton Dome and Deaf Smith 640 million dollars, between Deaf Smith and Davis Canyon 1127 million dollars, and between Davis Canyon and Hanford 2552 million dollars.

If the equivalent-consequence impacts shown in the fourth column are compared with the total equivalent impacts shown in the fifth column in Table 4-21, the reason for these differences becomes clear. Because the total cost differences among sites are in the billions of dollars and the differences in noncost impacts are equivalent to only 158 million dollars at most (the difference between the first-ranked Hanford site and the fifth-ranked Davis Canyon site in noncost performance-measure category), the differences in costs--especially repository costs--dominate the overall preclosure ranking.

Table 4-21 also shows the overall utility calculated for each site with Equation 4-1. As in Chapter 3 and as explained earlier in this chapter, the utility is expressed on a scale of 0 to 100, where higher utilities are more desirable. This alternative way of expressing preclosure results will facilitate the integration of postclosure and preclosure results in Chapter 5.

The stability of the base-case results was examined by sensitivity analyses involving changes in the level of impacts, in the value judgments, and in the form of the multiattribute utility function itself. Within the ranges estimated for possible impacts, the relative ranking of sites obtained for the base case is totally insensitive to any changes in the level of impacts except for costs. Furthermore, the ranking is insensitive to any reasonable changes in the value judgments or in the form of the utility function.

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Chapter 5

COMPOSITE ANALYSIS

This chapter combines the results of the postclosure and the preclosure multiattribute utility analyses to obtain an overall ranking of the sites. It also explores the sensitivity of that ranking to basic assumptions. Section 5.1 uses the logic of multiattribute utility analysis to formally aggregate the quantitative results. Section 5.2 summarizes the insights obtained from the analysis and presents the initial order of preference for sites for recommendation for characterization.

5.1 FORMAL AGGREGATION OF POSTCLOSURE AND PRECLOSURE RESULTS

Using the logic of the multiattribute utility analysis, the results of the postclosure and preclosure analyses can be formally aggregated. Given the independence assumptions discussed in Appendix G, the composite utility, which quantifies the estimated overall desirability of a site, can be expressed as

$$U_{comp} = k_{pre}U_{pre} + k_{post}[E(U_{post})], \qquad (5\text{-}1)$$

where U_{pre} is the preclosure utility of the site calculated from Equation 4-1, $E(U_{post})$ is the expected postclosure utility of the site calculated from Equation 3-4, and k_{pre} and k_{post} are scaling factors, or weights, that sum to 1. (The expected postclosure utility is the sum of the postclosure utilities estimated for various postclosure scenarios multiplied by the estimated probabilities of the scenarios.)

As explained in Appendix G, it is not easy to interpret the scaling factors, because they depend on the ranges of the performance measures; independent of their ranges, the scaling factors most emphatically cannot be used as indicators of the importance of the respective performance measure. The selection of specific values for the scaling factors requires value tradeoffs between preclosure and postclosure impacts. These value tradeoffs measure how much one is willing to give up on postclosure performance to gain a specific amount on preclosure performance. Before discussing this in detail, it is informative to conduct a sensitivity analysis over the entire range of values for the scaling factors k_{pre} and k_{post}.

Figure 5-1 presents the composite utilities obtained from the results of analyses for the preclosure and the postclosure periods. Figure 5-2 expands that part of the ranges of the scaling factors k_{pre} and k_{post} in which a change in the ranking of sites according to composite utility occurs. The base-case utility for preclosure performance is taken from Table 4-21, and the base-case expected utility for postclosure performance is taken from Table 3-6. The full range of possible relative weightings is considered, from the case where all the weight is given to the postclosure utility (k_{pre} = 0 and k_{post} = 1) to the case where all the weight is given to the preclosure utility (k_{pre} = 1 and k_{post} = 0).

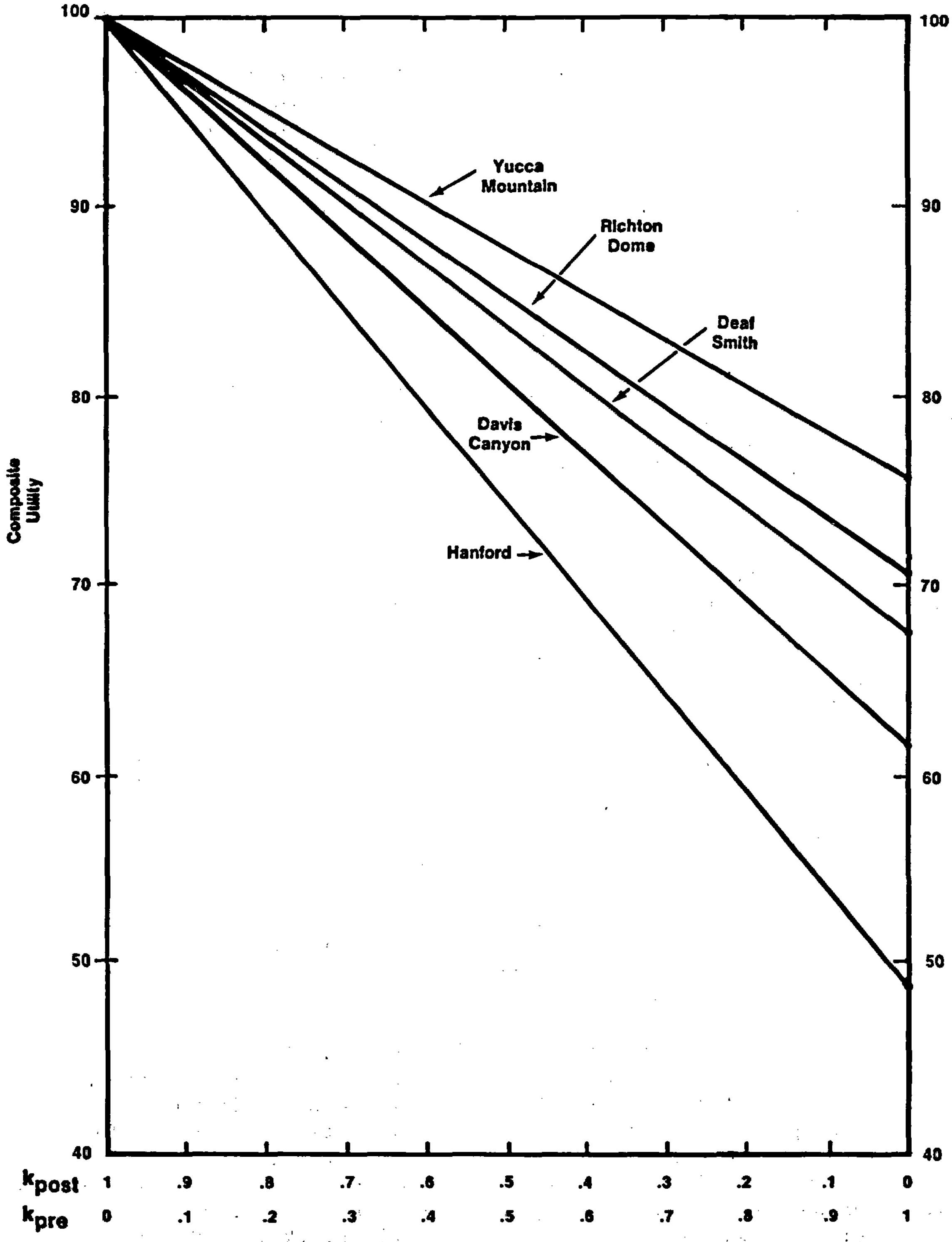

Figure 5-1. Composite utilities of sites for all possible preclosure-postclosure weightings and base-case assumptions.

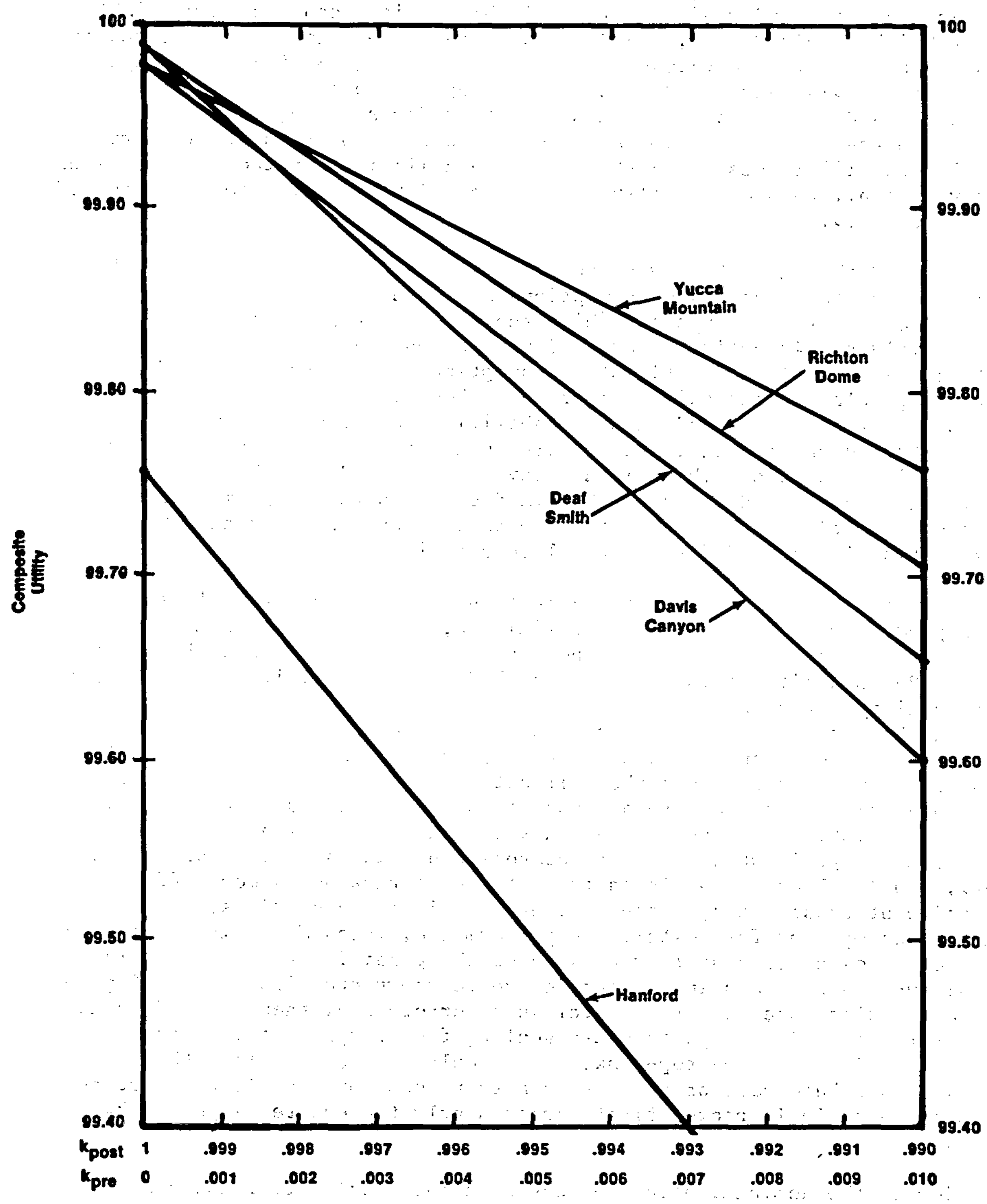

Figure 5-2. Site composite utilities for high postclosure weightings calculated under base-case assumptions.

It is clear from Figures 5-1 and 5-2 that the ranking of the sites remains the same for a wide range of weightings. Over most of the range of possible weightings, the order of overall desirability is Yucca Mountain, Richton Dome, Deaf Smith, Davis Canyon, and Hanford. When an extremely high weight is assigned to the expected postclosure utility (i.e., $k_{post} \geq .998$), the site ranking becomes Davis Canyon and Richton Dome (approximately tied for first), Yucca Mountain and Deaf Smith (approximately tied for second), and Hanford last. Because the differences among the expected postclosure utilities are very small, the differences among the composite utilities for the various sites are also very small when essentially all of the weight is given to the expected postclosure utility.

Figures 5-3 through 5-6 show composite utilities for the five sites when assumptions other than base-case assumptions are used. Figure 5-3 shows the results when optimistic assumptions (high scores and low probabilities for scenarios involving disruptive events and unexpected features) are used for the postclosure analysis and optimistic assumptions (low impact levels) are used for the preclosure analysis. Figure 5-4 shows the results when pessimistic assumptions (low scores and high probabilities for scenarios involving disruptive events and unexpected features) are used for the postclosure analysis and pessimistic assumptions (high impact levels) are used for the preclosure analysis. Figures 5-5 and 5-6 show the mixed cases in which optimistic or pessimistic assumptions are adopted for the postclosure analysis and the reverse assumption is adopted for the preclosure analysis.

Although the values of the scaling factors at which the overall ranking changes depend on whether base-case, pessimistic, or optimistic assumptions are used, certain patterns are clear and stable under a wide range of assumptions. 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 the postclosure utilities. This is so because it is ranked fifth for all sets of assumptions in both the preclosure and the 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 nearly 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 due to unexpected features. If pessimistic assumptions are used for postclosure performance, then Yucca Mountain is ranked first only if the postclosure scaling factor k_{post} is less than about .2; it is in the three top-ranked sites only if k_{post} is less than about .35. Under base-case or optimistic assumptions for postclosure performance, Yucca Mountain is ranked first across nearly the entire ranges of k_{pre} and k_{post}.

In view of the dominant effect of costs on the preclosure ranking of sites and the dominance of the preclosure utility over the postclosure utility in determining the overall ranking based on the composite utility, it is of interest to investigate what the overall rank order of the sites would be if differences in costs were not considered. Figure 5-7 shows the utilities calcu-

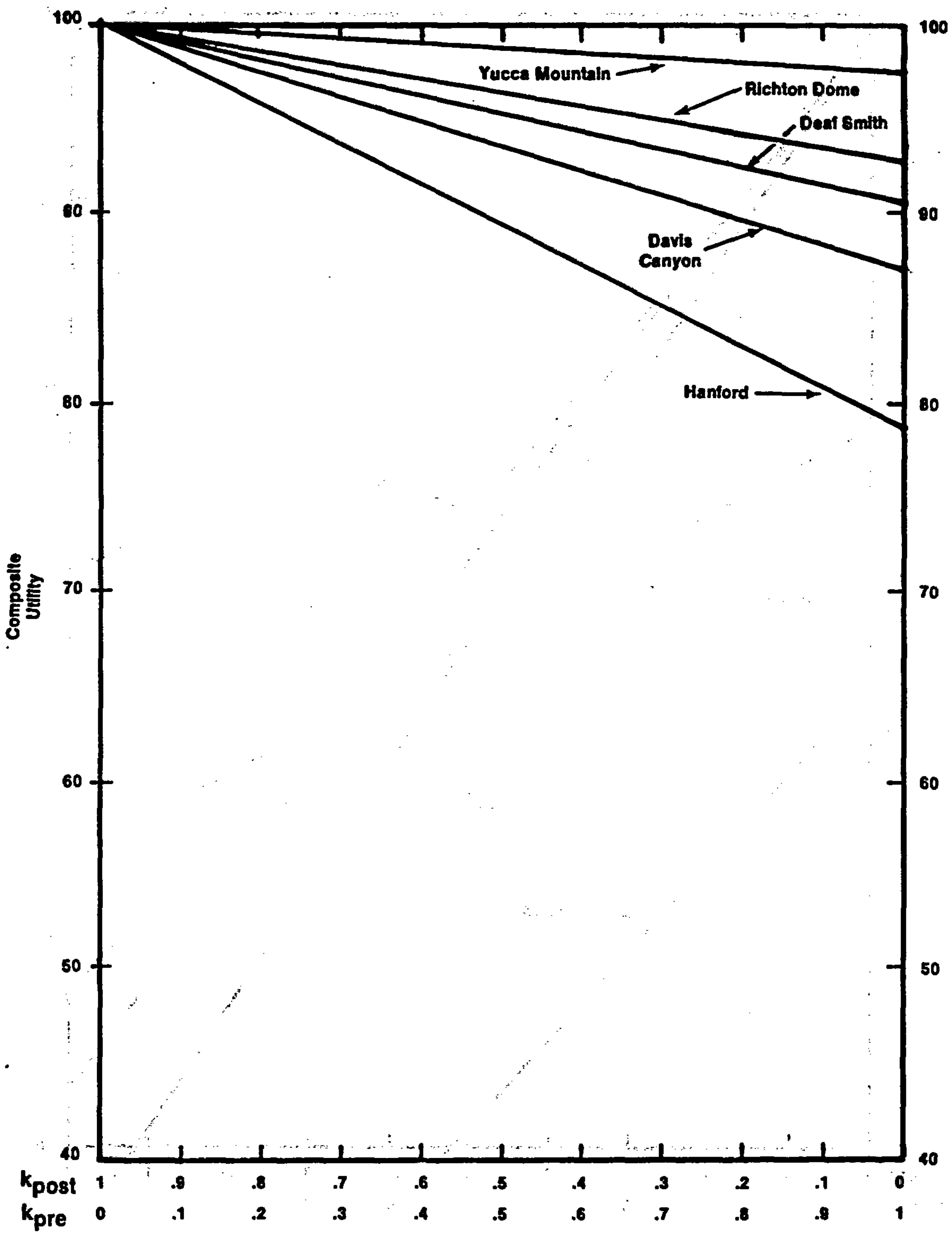

Figure 5-3. Site composite utilities calculated under optimistic assumptions for postclosure and preclosure.

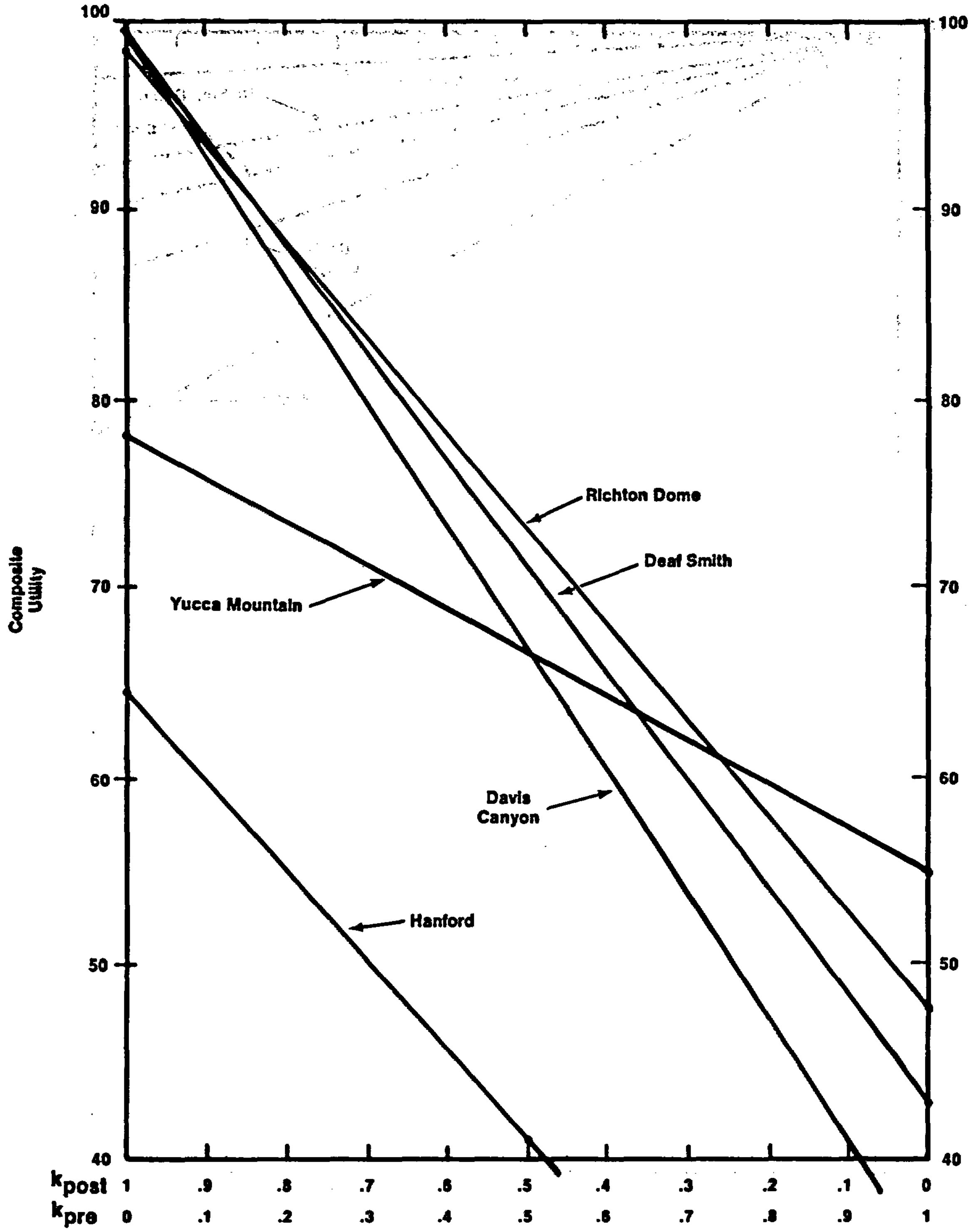

Figure 5-4. Site composite utilities calculated under pessimistic assumptions for postclosure and preclosure.

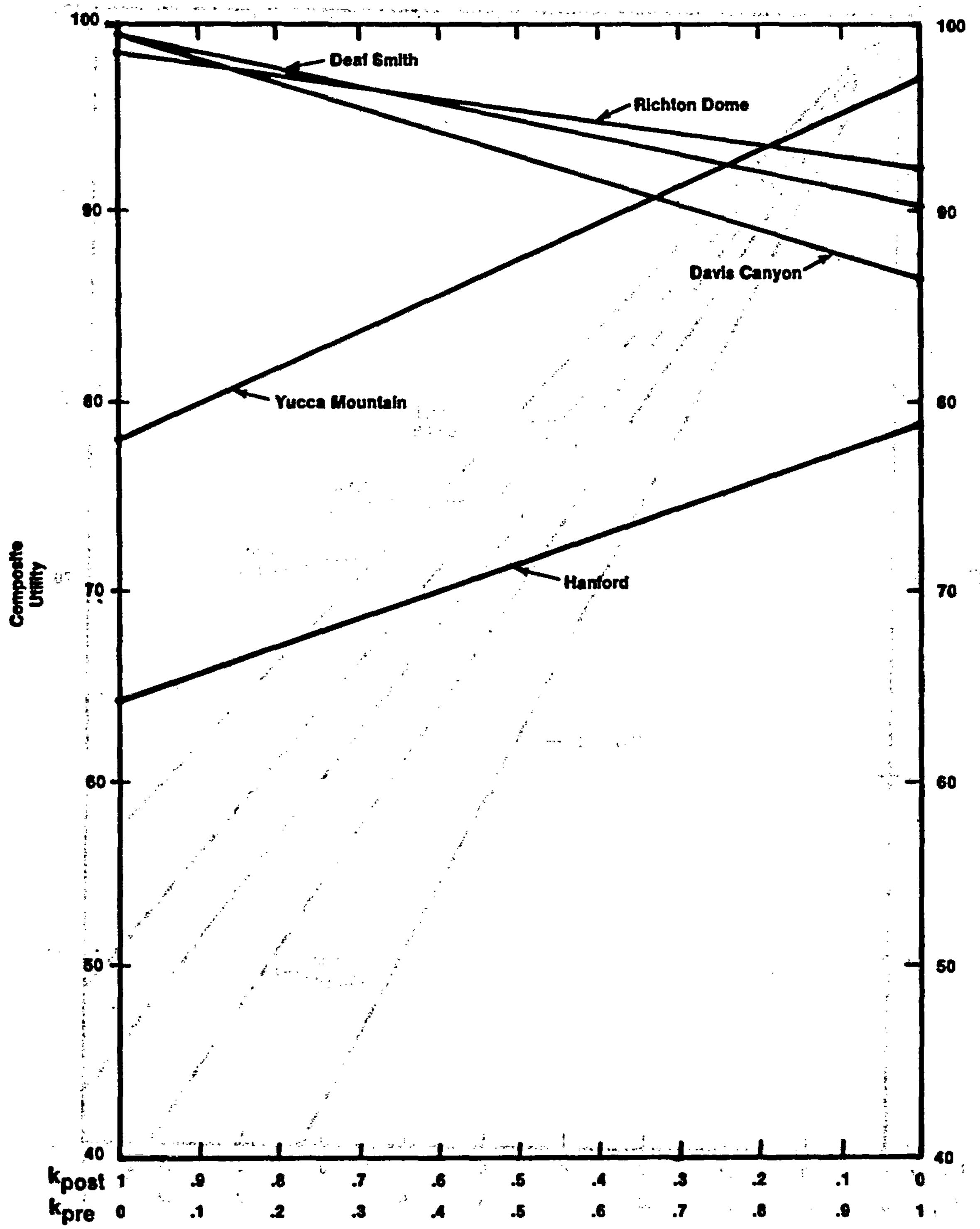

Figure 5-5. Site composite utilities calculated under pessimistic assumptions for postclosure and optimistic assumptions for preclosure.

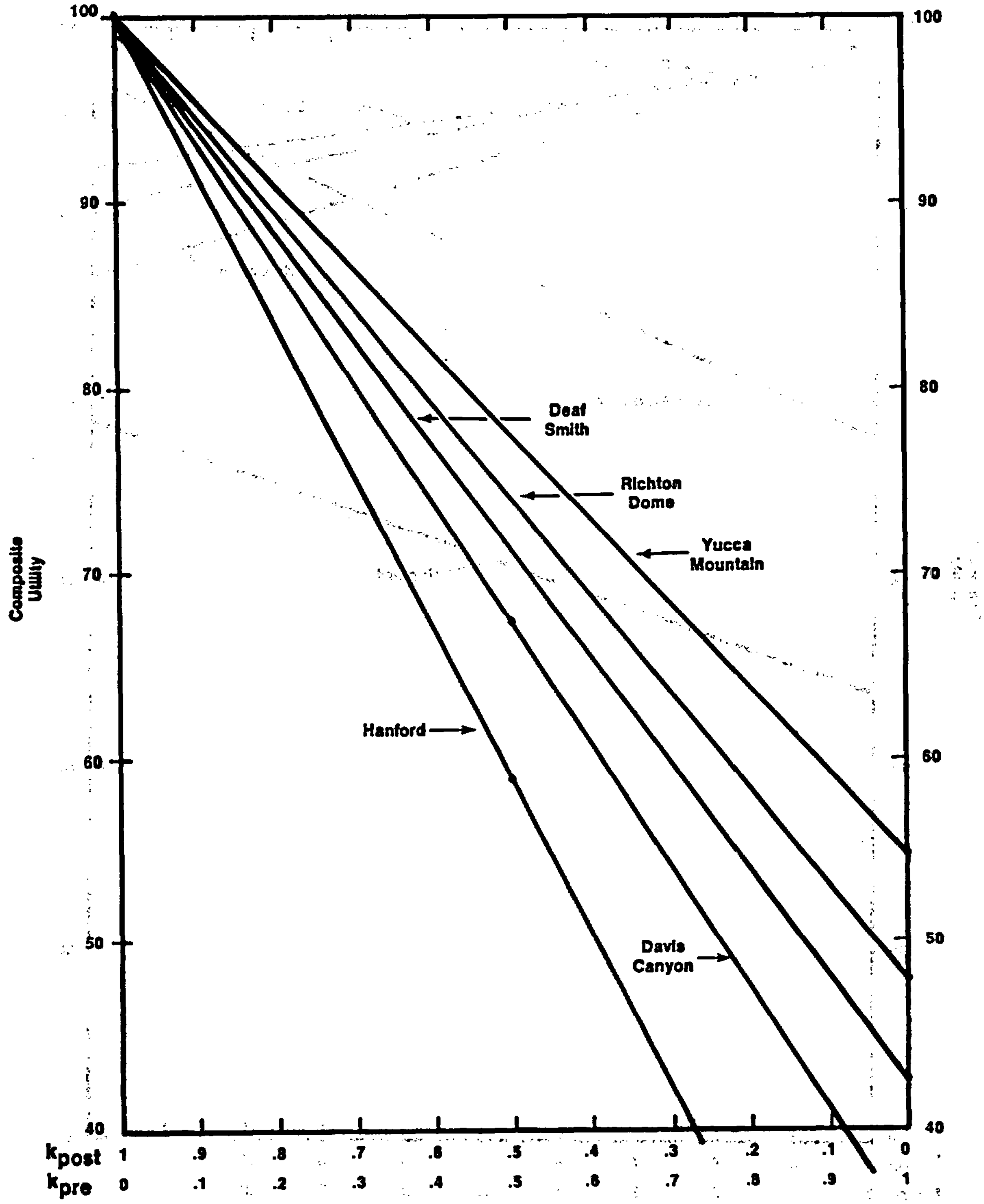

Figure 5-6. Site composite utilities calculated under optimistic assumptions for postclosure and pessimistic assumptions for preclosure.

lated for each site when repository and transportation costs (X_{13} and X_{14}) are identical for all sites and are set at the lowest levels deemed possible for the nominated sites. In this case, preclosure differences no longer dominate the overall rank order, and the ranking depends critically on the scaling factors k_{pre} and k_{post}. If k_{post} is less than about .57, the three-top ranked sites are Yucca Mountain, Deaf Smith, and Hanford. If a weight higher than .57 is assigned to the postclosure utility, the three top-ranked sites are Yucca Mountain, Deaf Smith, and Richton Dome. The rankings in this case are the rankings that would be obtained if only health-and-safety, socioeconomic, and environmental objectives were considered.

Figure 5-8 shows the results obtained when socioeconomic impacts, environmental impacts, and costs are assumed to be identical for all sites. Specifically, all sites are assumed to have no socioeconomic and environmental impacts, and the repository and waste-transportation costs for all sites are set at the lowest level deemed possible for the nominated sites. Thus, only health-and-safety objectives are considered. In this case, the three top-ranked sites are Richton, Deaf Smith, and Davis Canyon, regardless of the preclosure-to-postclosure weighting. From Figures 5-7 and 5-8 it can be seen that costs account for the major differences in composite utilities. When costs or costs plus socioeconomic and environmental impacts are not considered, the composite utilities of the sites are comparable, indicating that the sites are nearly equal in desirability, regardless of the values assigned to the scaling factors k_{pre} and k_{post}.

Because of the sensitivity of the rankings to the relative values of k_{pre} and k_{post}, it is of interest to consider the reasonableness of different numerical values. As in the case with the scaling factors used in Chapters 3 and 4, the scaling factors k_{pre} and k_{post} must be based on a value judgment, in this case a value tradeoff between postclosure performance and preclosure performance. The value of k_{pre} determines the increase in composite utility that would result from increasing the preclosure utility by one utile--that is, by one unit. An increase of one utile in the preclosure utility might be produced in a variety of ways. For example, from Chapter 4, a one-utile increase in the preclosure utility would be produced by a $200 million decrease in repository costs, by a reduction of 50 statistical fatalities in the public, or by a $100 million decrease in costs coupled with a reduction of 25 statistical fatalities in the public. Similarly, k_{post} determines the increase in composite utility that would result from increasing the postclosure utility by one utile. According to Chapter 3, a one-utile increase in the postclosure utility would be produced if the cumulative radionuclide releases were decreased by an amount equal to one one-hundredth of the limits allowed by the EPA standards for each 10,000-year interval in 100,000 years. A decision to set the scaling-factor values at $k_{pre} = k_{post} = .5$, for example, would be equivalent to the value judgment that a preclosure difference of $100 million in repository costs and 25 statistical fatalities is about as significant as a postclosure release difference of one one-hundredth of the EPA limits during each 10,000-year interval for 100,000 years.

To better judge whether particular numerical values for k_{pre} and k_{post} are reasonable, it is helpful to select convenient measures for summarizing preclosure and postclosure performance and to consider whether the tradeoffs between these measures are reasonable. This tradeoff is most

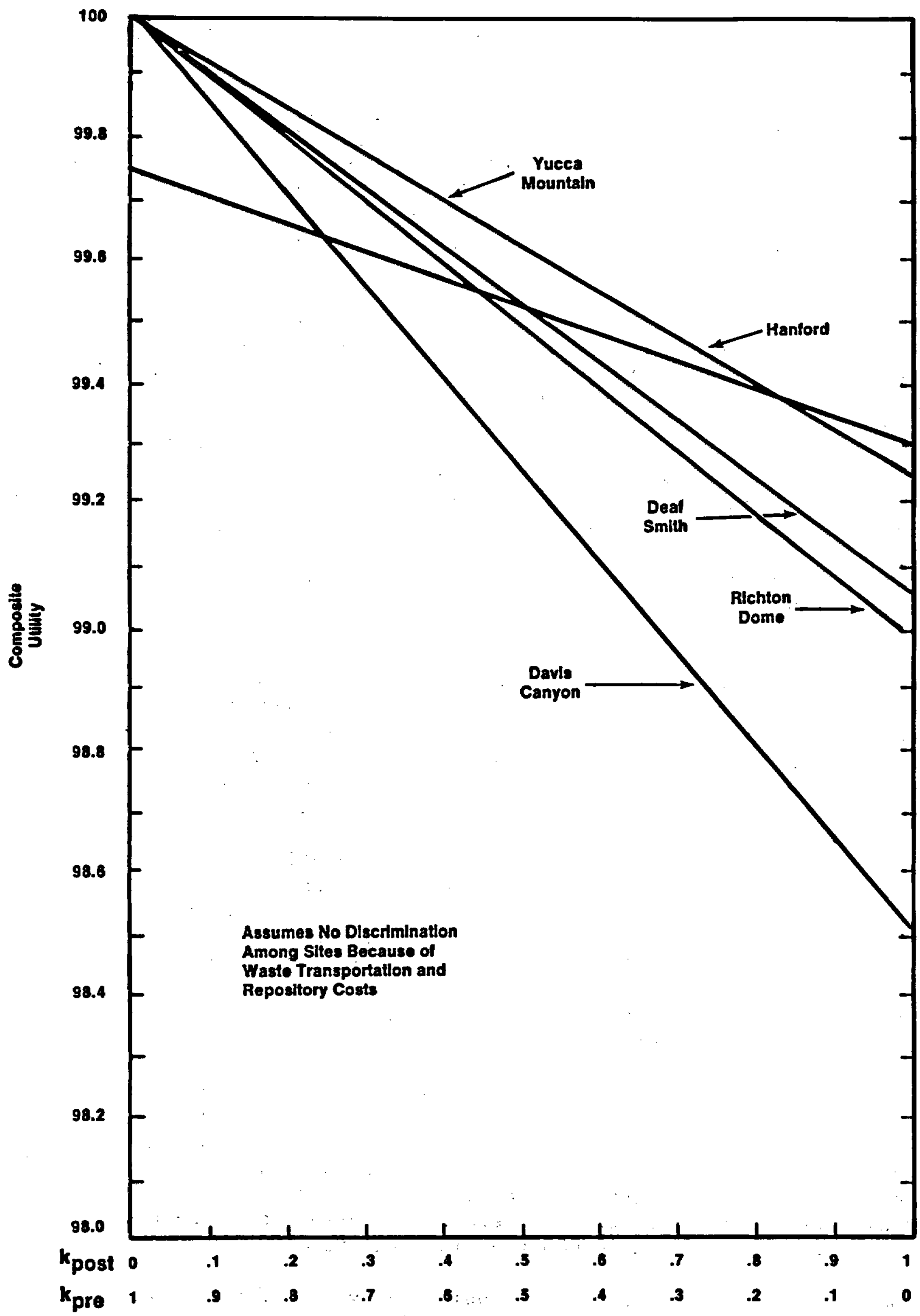

Figure 5-7. Composite utilities of sites as a function of preclosure-to-postclosure weighting for base-case conditions, assuming identical waste-transportation and repository costs for all sites.

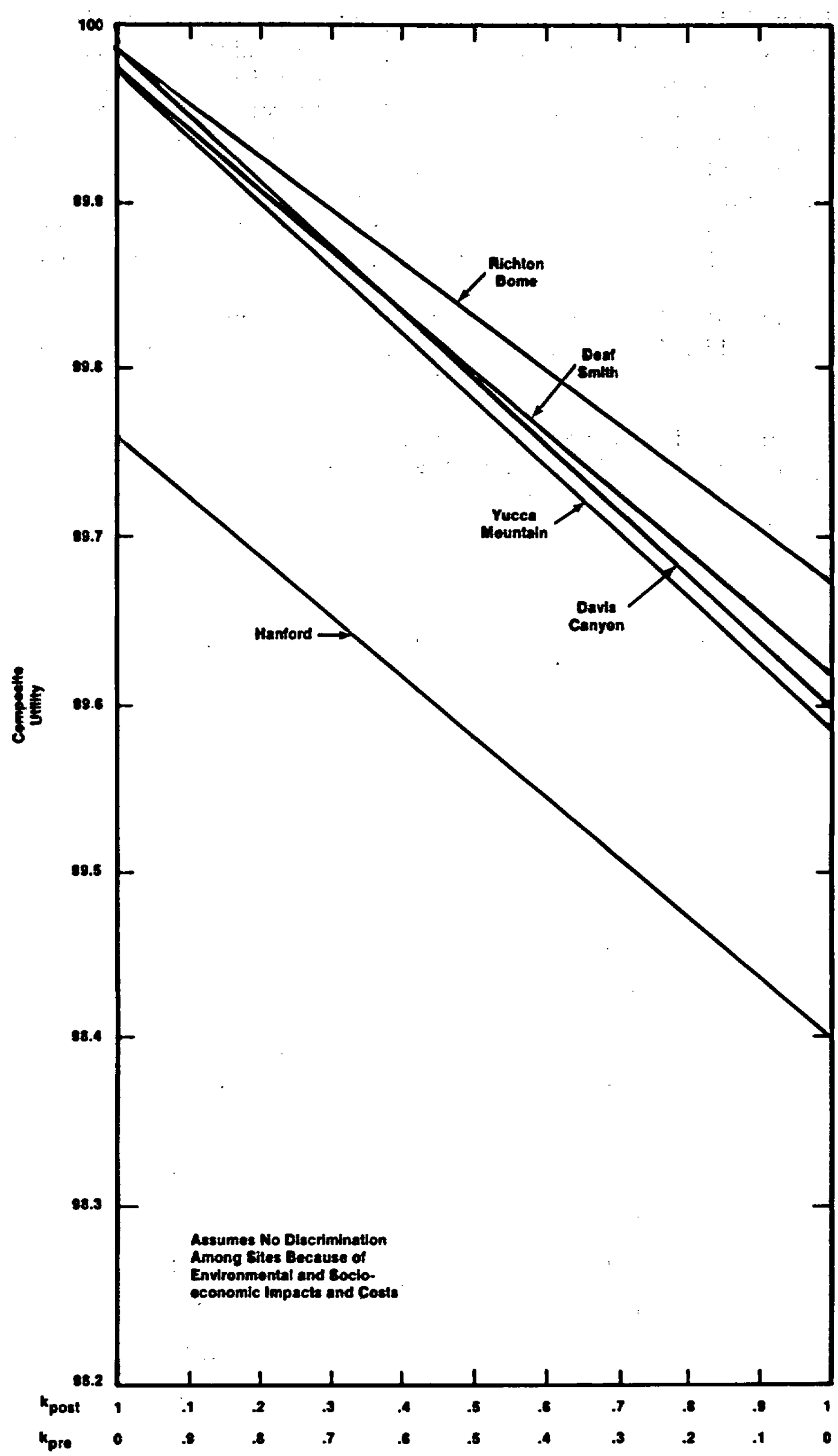

Figure 5-8. Composite utilities of sites as a function of preclosure-to-postclosure weighting for base-case conditions, assuming no environmental and socioeconomic impacts and identical waste-transportation and repository costs for all sites.

conveniently considered in terms of preclosure and postclosure radiological safety. Specifically, if the preclosure radiological safety is expressed in terms of cancer fatalities and the postclosure radiological safety is expressed in terms of cumulative radionuclide releases, the value tradeoff can be expressed as the postclosure radionuclide releases y (occurring in the first 10,000 years after repository closure) that would be just as undesirable as 10 additional preclosure cancer fatalities. Table 5-1 shows the values for the scaling factors k_{pre} and k_{post} that correspond to several different tradeoffs. These values for the scaling factors were calculated as follows:

1. The preclosure-utility decrease from an additional 10 cancer fatalities in the public is found from Equation 4-1 to be (1/200)(4)(10) = 0.2.

2. The postclosure-utility decrease from an increase in radionuclide releases y during the first 10,000 years is found from Equation 3-3 to be (0.526)(100)(y) = 52.6y, where y is expressed as a fraction of the EPA limits.

Table 5-1. Value tradeoffs between preclosure radiological health effects and postclosure radionuclide releases implied by various values of the scaling factors k_{pre} and k_{post}

k_{pre}	[b] k_{post}	Postclosure release y deemed as undesirable as 10 preclosure fatalities[a] (fraction of EPA limits[c])
1.0	0.0	—
0.99	0.01	0.38
0.9	0.1	0.03
0.8	0.2	0.02
0.7	0.3	0.01
0.6	0.4	0.006
0.5	0.5	0.004
0.4	0.6	0.003
0.3	0.7	0.002
0.2	0.8	0.001
0.1	0.9	0.0004
0.01	0.99	0.00004
0.0	1.0	—

[a] Preclosure cancer fatalities incurred by the public from the repository.
[b] Since the scaling factors sum to 1, $k_{post} = 1 - k_{pre}$.
[c] Primary containment requirements of 10 CFR Part 191, Subpart B.

3. The postclosure-versus-preclosure tradeoff implies that each of the above changes produces the same decrease in the composite utility. From Equation 5-1, therefore,

$$k_{pre}(0.2) = k_{post}(52.6y),$$

which implies that

$$y = 0.0038(k_{pre}/k_{post}).$$

Table 5-1 shows, for various values of the scaling factors, the postclosure radionuclide releases y that would be regarded as undesirable as 10 preclosure cancer fatalities in the public.

The reasonableness of the various value tradeoffs in Table 5-1 can be seen more easily if a relationship is assumed between postclosure releases and postclosure health effects. As noted in Chapter 3, in 40 CFR Part 191 the U.S. Environmental Protection Agency adopted the assumption that, for each 1000 metric tons of heavy metal (MTHM), cumulative releases at the level the EPA limits would result in 10 deaths from cancer. Because a repository at any of the nominated sites is assumed to accept 70,000 MTHM, releases at the level of the EPA limits would produce approximately 700 cancer fatalities in 10,000 years.

Table 5-2 shows the tradeoff between preclosure and postclosure cancer fatalities that is implied by various values of the scaling factors if the radionuclide releases shown in Table 5-1 are converted to postclosure fatalities under the EPA assumption. Because the EPA relationship between postclosure releases and cancer fatalities probably overestimates the fatalities, the implied value tradeoff is likely to be a lower bound on the relative significance of postclosure fatalities. It is noted that the selection of scaling-factor values that imply a willingness to trade off a great many postclosure fatalities (i.e., values at the top portion of Table 5-2) may be inappropriate in view of the requirement in the DOE siting guidelines that postclosure considerations be given greater importance than preclosure considerations.

As can be seen from Figures 5-1, 5-2, 5-3, and 5-6, the composite utilities imply that the overall site ranking is Yucca Mountain, Richton Dome, Deaf Smith, Davis Canyon, and Hanford for all postclosure weights equal to or less than .99, provided that the postclosure performance is assumed to be at the base-case level or optimistic (regardless of the preclosure assumptions). Values of k_{post} greater than .99 would, according to Table 5-2, imply a willingness to accept more than 350 preclosure cancer fatalities to avoid 1 postclosure cancer fatality. If pessimistic assumptions are used for postclosure performance, Yucca Mountain falls out as the overall preferred site when the implied value tradeoff between postclosure and preclosure cancer fatalities is approximately 1:1 (i.e., k_{post} = .21). It drops from among the three top-ranked sites when, under pessimistic assumptions, this implied value tradeoff is such that approximately two preclosure fatalities would be accepted to avoid one postclosure fatality (i.e., k_{post} = .35).

Table 5-2. Value tradeoffs between preclosure and postclosure radiological health effects implied by various values of the scaling factors k_{pre} and k_{post}

k_{pre}	[a]k_{post}	Implied value tradeoff between preclosure and postclosure cancer fatalities
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, $k_{post} = 1 - k_{pre}$.

In interpreting the significance of computed differences in composite utilities, it is necessary to consider the values of the scaling factors k_{pre} and k_{post}. For any given values of these scaling factors, the significance of a given difference in utilities can be deduced from the meaning of preclosure and postclosure utilities. For example, suppose that values of .5 were judged reasonable for k_{pre} and k_{post}, and suppose that two sites had composite utilities that differed by 0.1 utile. A decrease of one utile in postclosure utility corresponds to a decrease in desirability comparable to that produced by an increase in radionuclide releases equal to one one-hundredth of the EPA limits, assuming that these releases occur during each 10,000-year interval for 100,000 years. A decrease of one utile in preclosure utility corresponds to a decrease in desirability comparable to that produced by an additional $200 million in costs (equivalent to, for example, an additional 50 preclosure statistical radiological fatalities suffered by the public). Thus, given the preclosure and postclosure weights selected above, a difference of 0.1 utile in the composite utilities corresponds to a difference in desirability comparable to that of decreasing postclosure releases by one one-thousandth of the EPA limits and simultaneously decreasing by five the number of preclosure radiological fatalities in the public. Alternatively, the difference in composite utilities corresponds to a difference in desirability comparable to that of decreasing preclosure radiological fatalities in the public by 10 and leaving postclosure radionuclide releases unchanged.

5.2 INITIAL ORDER OF PREFERENCE FOR SITES FOR RECOMMENDATION FOR CHARACTERIZATION

As indicated in Chapters 1 and 2, the purpose of the decision-aiding methodology is to provide insights as to the comparative advantages and disadvantages of the five sites and, in so doing, to determine an initial order of preference for sites for recommendation for characterization. With reference to the postclosure, preclosure, and composite analyses of sites presented in this report, the major insights derived from the multiattribute utility analysis are summarized below.

Postclosure analysis

- All five sites appear capable of providing exceptionally good radiological protection for future populations for at least 100,000 years after closure.

- The Davis Canyon, Deaf Smith, Richton Dome, and Yucca Mountain sites appear to be virtually indistinguishable in terms of the expected postclosure performance. The Hanford site is just discernibly less favorable than the other four sites, but its performance is still far above the threshold of acceptability established by the EPA. It is noted that the primary containment requirements of the EPA--the criterion of acceptability used here--provide a very stringent standard for protecting public health and safety: the risk to the public is not to exceed the risks that would have existed if the uranium ore that was the source of the waste had not been mined to begin with.

- The confidence in the performance of the three salt sites (Davis Canyon, Deaf Smith, and Richton Dome) is exceptionally high, and it is higher than that for the nonsalt sites (Hanford and Yucca Mountain).

- The overall postclosure ranking of Davis Canyon, Richton Dome, Deaf Smith, Yucca Mountain, and Hanford is stable over a wide range of sensitivity analyses.

Preclosure analysis

- With regard to preclosure health and safety, the site rankings are Richton Dome, Deaf Smith, Davis Canyon, Yucca Mountain, and Hanford. The differences among the sites are largely attributable to waste transportation and to nonradiological repository-worker fatalities due to accidents.

- With regard to environmental and socioeconomic impacts, the site rankings are Hanford, Yucca Mountain, Deaf Smith, Richton Dome, and Davis Canyon. The difference between sites is greater than the difference on health-and-safety impacts. However, this difference is relatively small in comparison with differences in total costs.

- With regard to total costs, the site rankings are Yucca Mountain, Richton Dome, Deaf Smith, Davis Canyon, and Hanford. The difference between the most favorable site and the least favorable site is equal to 4380 million (4.38 billion) dollars.

- Considering all preclosure impacts, the overall ranking of sites is Yucca Mountain, Richton Dome, Deaf Smith, Davis Canyon, and Hanford. This ranking is stable over a wide range of sensitivity analyses.

- The overall preclosure ranking is mainly attributable to the large differences among sites in total costs. The fact that cost is the major preclosure discriminator can be explained by the screening process that led to the nominated sites (see Chapter 1). Because the criteria used in screening were concerned with health and safety and the environment, but not with costs, sites expected to perform poorly on objectives other than costs have already been screened out.

Composite analysis

- Because the differences among sites in postclosure performance are very small and the differences in preclosure performance are relatively large, the overall composite results are largely a reflection of the preclosure impacts and thus of costs.

- The composite overall ranking of sites is basically insensitive to the relative values of the scaling factors k_{post} and k_{pre}.

- The composite overall ranking under a wide range of assumptions is Yucca Mountain, Richton Dome, Deaf Smith, Davis Canyon, and Hanford.

It follows, therefore, that the overall ranking of sites is Yucca Mountain, Richton Dome, Deaf Smith, Davis Canyon, and Hanford. This ranking is stable except for the most extreme assumptions about postclosure performance combined with the most extreme weightings of postclosure performance versus preclosure performance.

As noted above, this overall ranking of sites is largely a reflection of differences in costs. This dependence on costs was recognized by the Board on Radioactive Waste Management of the National Academy of Sciences in its comments on the application of the methodology (see attachment to Appendix H, letter dated April 10, 1986, p. 4): "On the basis of the Board's review of the application to a single site, it appears that the expected total repository and transportation costs will have a major, if not controlling, effect on the rankings under pre-closure factors." As shown in Figure 5-7, when repository and transportation costs are not discriminating and postclosure performance is weighted up to about .57, the three top-ranked sites are Yucca Mountain, Deaf Smith, and Hanford. When higher weight is given to postclosure performance, the three top-ranked sites are Yucca Mountain, Deaf Smith, and Richton.

In view of the requirements of the siting guidelines that costs be among the factors given the least importance among preclosure considerations, the above rankings must be carefully considered. The need to consider carefully the results obtained with the methodology was also recognized by the Board in the above-cited letter: "This recognition of the heavy dependence on cost reinforces the Board's judgment that the principal usefulness of the multi-attribute utility method is to illuminate the factors involved in a decision, rather than to make the decision itself." Furthermore, as explained in Section 2.1, the site-recommendation decision is analogous to a portfolio-selection problem because the DOE is not choosing a single site for repository development; rather, the DOE must choose, from a suite of five well-qualified sites, three sites for characterization. Combinations of three sites possess properties that cannot be attributed to individual sites, such as diversity of geohydrologic settings and rock types.

GLOSSARY OF TERMS

Accessible environment	The atmosphere, the land surface, surface water, oceans, and the portion of the lithosphere that is outside the controlled area.
Act	The Nuclear Waste Policy Act of 1982.
Active fault	A fault along which there is recurrent movement, which is usually indicated by small, periodic displacements or seismic activity.
Active institutional controls	(1) Controlling access to a disposal site by any means other than passive institutional controls; (2) performing maintenance operations or remedial actions at a site; (3) controlling or cleaning up releases from a site; or (4) monitoring parameters related to disposal system performance.
Affected area	Either the area of socioeconomic impact or the area of environmental impact, each of which will vary in size among potential repository sites.
Affected Indian Tribe	Any Indian (1) within whose reservation boundaries a repository for radioactive waste is proposed to be located or (2) whose federally defined possessory or usage rights to other lands outside the reservation boundaries arising out of congressionally ratified treaties may be substantially and adversely affected by the locating of such a facility: provided that the Secretary of the Interior finds, upon the petition of the appropriate governmental officials to the Tribe, that such effects are both substantial and adverse to the Tribe.
Aquifer	A formation, a group of formations, or a part of a formation that contains sufficient saturated permeable material to yield significant quantities of water to wells and springs.
Barrier	Any material or structure that prevents or substantially delays the movement of water or radionuclides.
Basalt	A dark to medium dark igneous rock usually formed from lava flows and composed chiefly of calcic plagioclase and clinopyroxene in a glassy or fine-grained ground mass.
Candidate site	An area, within a geohydrologic setting, that is recommended by the Secretary of Energy under

Section 112 of the Act for site characterization, approved by the President under Section 112 of the Act for characterization, or undergoing site characterization under Section 113 of the Act.

Canister	A metal vessel for consolidated spent fuel or solidified high-level waste. Before emplacement in the repository, the canister will be encapsulated in a disposal container.
Cenozoic	The latest of the eras into which geologic time, as recorded by the stratified rocks of the earth's crust, is divided; this era is considered to have begun about 65 million years ago.
Certain equivalent	That certain value, expressed in terms of the units used to measure an uncertain impact, that a decisionmaker is just willing to accept in lieu of the uncertain impact.
Closure	Final backfilling of the remaining open operational areas of the underground facility and boreholes after the termination of waste emplacement, culminating in the sealing of shafts.
Containment	The confinement of radioactive waste within a designated boundary.
Container	Synonym for the metal envelope in the waste package that provides the primary containment function of the waste package and is designed to meet the containment requirements of 10 CFR Part 60.
Controlled area	(1) A surface location, to be identified by passive institutional controls, that encompasses no more than 100 square kilometers and extends horizontally no more than five kilometers in any direction from the outer boundary of the original location of the radioactive wastes in a disposal system; and (2) the subsurface underlying such a surface location.
Cumulative releases of radionuclides	The total number of curies of radionuclides entering the accessible environment in any 10,000-year period, normalized on the basis of radiotoxicity in accordance with 40 CFR Part 191. The peak cumulative release of radionuclides refers to the 10,000-year period during which any such release attains its maximum predicted value.
Darcian flow	Flow of fluids that is described by a numerical formulation of Darcy's law.

Decommissioning	The permanent removal from service of surface facilities and components necessary for preclosure operations only, after repository closure, in accordance with regulatory requirements and environmental policies.
Disposal	The emplacement in a repository of high-level radioactive waste, spent nuclear fuel, or other highly radioactive material with no foreseeable intent of recovery, whether or not such emplacement permits the recovery of such waste, and the isolation of such waste from the accessible environment.
Disqualifying condition	A condition that, if present at a site, would eliminate that site from further consideration.
Disutility	A quantitative measure of undesirability.
DOE	The U.S. Department of Energy.
dome	A diapiric or piercement structure with a central plug that has risen through the enclosing sediments from a deep mother bed of salt.
EA	Environmental assessment.
Effective porosity	The amount of interconnected pore space and fracture openings available for the transmission of fluids, expressed as the ratio of the volume of interconnected pores and openings to the volume of rock.
Engineered-barrier system	The manmade components of a disposal system designed to prevent the release of radionuclides from the underground facility or into the geohydrologic setting. Such term includes the radioactive-waste form, radioactive-waste canisters, materials placed over and around such canisters, any other components of the waste package, and barriers used to seal penetrations in and into the underground facility.
Environmental assessment	The document required by Section 112(b)(E) of the Nuclear Waste Policy Act of 1982.
EPA	The U.S. Environmental Protection Agency.
EPA limits	The radionuclide release limits for the containment requirements (cumulative releases to the accessible environment for 10,000 years after disposal) as specified by Table 1 and Notes 1 through 6 of Appendix A of 40 CFR Part 191.

EPA standard	Part 191 of Title 40 of the Code of Federal Regulations--Environmental Standards for the Management and Disposal of Spent Fuel, High-Level and Transuranic Radioactive Wastes.
Equivalent releases	A release rate per 10,000-year interval (at a given site) that, if it were to occur for 100,000 years, the site would have the same expected utility as that calculated for the given site. The equivalent releases for a site are the certain equivalent of the uncertain releases from that site (see "certain equivalent").
Expected releases	Expected value of releases.
Equivalent-consequence impact	As used in this report, a monetary equivalent of an adverse impact expressed in millions of dollars.
Expected repository performance	The manner in which the repository is predicted to function, considering those conditions, processes, and events that are likely to prevail or may occur during the time period of interest.
Expected utility	Expected value of an uncertain utility.
Expected value	A summary measure for an uncertain numerical variable obtained by weighting all possible outcomes by their probabilities and summing.
Facility	Any structure, system, or system component, including engineered barriers, created by the DOE to meet repository-performance or functional objectives.
Fault	A fracture or a zone of fractures along which there has been displacement of the sides relative to one another and parallel to the fracture or zone of fractures.
Faulting	The process of fracturing and displacement that produces a fault.
Favorable condition	A condition that, though not necessary to qualify a site, is presumed, if present, to enhance confidence that the qualifying condition of a particular guideline can be met.
Gassy mine	Underground operation in which the content of noxious or explosive gasses has been shown to exceed levels specified in 30 CFR Part 57 by the Mine Safety and Health Administration.
Geohydrologic setting	The system of geohydrologic units that is located within a given geologic setting.

Geohydrologic system	The geohydrologic units within a geologic setting, including any recharge, discharge, interconnections between units, and any natural or man-induced processes or events that could affect ground-water flow within or among those units.
Geohydrologic unit	An aquifer, a confining unit, or a combination of aquifers and confining units comprising a framework for a reasonably distinct geohydrologic system.
Geologic repository	A system, requiring licensing by the Nuclear Regulatory Commission, that is intended to be used, or may be used, for the disposal of radioactive waste in excavated geologic media. A geologic repository includes (1) the geologic-repository operations area and (2) the portion of the geologic setting that provides isolation of the radioactive waste and is located within the controlled area.
Geologic setting	The geologic, hydrologic, and geochemical systems of the region in which a geologic-repository operations area is or may be located.
Geomorphic processes	Geologic processes that are responsible for the general configuration of the earth's surface, including the development of present land forms and their relationships to underlying structures, and are responsible for the geologic changes recorded by these surface features.
Great Basin	A subdivision of the Basin and Range province, located in southern Nevada in a broad desert region. The Yucca Mountain site is in the Great Basin.
Ground water	All subsurface water as distinct from surface water.
Ground-water flux	The rate of ground-water flow per unit area of porous or fractured media measured perpendicular to the direction of flow.
Ground-water sources	Aquifers that have been or could be economically and technologically developed as sources of water in the foreseeable future.
Ground-water-travel time	The time required for a unit volume of ground water to travel between two locations. The travel time is the length of the flow path divided by the velocity, where velocity is the average ground-water flux passing through the

cross-sectional area of the geologic medium through which flow occurs, perpendicular to the flow direction, divided by the effective porosity along the flow path. If discrete segments of the flow path have different hydrologic properties, the total travel time will be the sum of the travel times for each discrete segment.

Guidelines	Part 960 of Title 10 of the Code of Federal Regulations—General Guidelines for the Recommendation of Sites for the Nuclear Waste Repositories.
Hanford Site	A DOE reservation covering nearly 600 square miles in south-central Washington. A portion of this reservation has been identified as a potentially acceptable site in basalt and is called the "Hanford site" or the "reference repository location."
Heavy metal	All uranium, plutonium, or thorium placed into a nuclear reactor.
High-level waste	The highly radioactive material resulting from the reprocessing of spent nuclear fuel, including liquid waste produced directly in reprocessing and any solid material derived from such liquid waste that contains fission products in sufficient concentrations; other highly radioactive material that the Nuclear Regulatory Commission, consistent with existing law, determined by rule to require permanent isolation.
Host rock	The geologic medium in which the waste is emplaced, specifically the geologic materials that directly encompass and are in close proximity to the underground facility.
Hydraulic conductivity	The volume of water that will move through a medium in a unit of time under a unit hydraulic gradient through a unit area measured perpendicular to the direction of flow.
Hydraulic gradient	A change in the static pressure of ground water, expressed in terms of the height of water above a datum, per unit of distance in a given direction.
Hydrologic process	Any hydrologic phenomenon that exhibits a continuous change in time, whether slow or rapid.
Hydrologic properties	Those properties of a rock that govern the entrance of water and the capacity to hold, transmit, and deliver water, such as porosity,

effective porosity, specific retention, permeability, and the directions of maximum and minimum permeabilities.

Igneous activity	The emplacement (intrusion) of molten rock material (magma) into material in the Earth's crust or the explosion (extrusion) of such material onto the earth's surface or into its atmosphere or surface water.
Impact level	An indication of the degree of impact.
Indifferent	Equally preferable; that is, such that there is no preference between two or more choices.
Influence diagram	A graphic diagram illustrating the various factors that influence the degree to which an objective is met and the relationships among such factors.
Isolation	Inhibiting the transport of radioactive material so that the amounts and concentrations of this material entering the accessible environment will be kept within prescribed limits.
Judgmental probability	A quantitative expression of likelihood based on personal belief and obeying the axioms of probability theory. Judgmental probabilities are equal to objective probabilities acceptable to the assessor for a substitute gamble.
Lithosphere	The solid part of the earth, including any ground water contained within it.
Lottery	A mutually exclusive and collectively exhaustive set of possible consequences and the probability of each consequence.
Maximally exposed individual	A hypothetical person who is exposed to a release of radioactivity in such a way that he receives the maximum possible individual radiation dose or dose commitment. For instance, if the release is a puff of contaminated air, the maximally exposed individual is a person at the point of the largest ground-level concentration and stays there during the whole time the contaminated-air cloud remains above.
Member of the public	Any individual who is not engaged in operations involving the management, storage, and disposal of radioactive waste. A worker so engaged is a member of the public except when on duty at the geologic-repository operations area.

Millirem	1 millirem is 1/1,000 of a rem.
Mitigation	(1) Avoiding the impact altogether by not taking a certain action or parts of an action; (2) minimizing impacts by limiting the degree or magnitude of the action and its implementation; (3) rectifying the impact by repairing, rehabilitating, or restoring the affected environment; (4) reducing or eliminating the impact over time by preservation and maintenance operations during the life of the action; or (5) compensating for the impact by replacing or providing substitute resources or environments.
Model	A conceptual description and the associated mathematical representation of a system, subsystem, component, or condition that is used to predict changes from a baseline state as a function of internal and/or external stimuli and as a function of time and space.
MTHM	Metric tons of heavy metal.
NRC	The U.S. Nuclear Regulatory Commission.
Nevada Test Site	An area in Clark and Nye Counties in southern Nevada; it is dedicated to the underground testing of nuclear weapons.
Paradox Basin	A 25,900-square-kilometer (10,000-square-mile) area in southeastern Utah and southwestern Colorado; it is underlain by bedded salt and a series of salt-core anticlines. The Davis Canyon site is in the Paradox Basin.
Pasco Basin	A structural and topographic basin in the western Columbia Plateau. The Hanford Site and the reference repository location are in the Pasco Basin.
Passive institutional control	(1) Permanent markers placed at a disposal site, (2) public records and archives, (3) government ownership and regulations regarding land and resource use, and (4) other methods of preserving knowledge about the location, design, and contents of a disposal system.
Perched ground water	Unconfined ground water separated from an underlying body of ground water by an unsaturated zone. Its water table is a perched water table. Perched ground water is held up by a perching bed whose permeability is so low that water percolating downward through it is not able to bring water in the underlying unsaturated zone above atmospheric pressure.

Performance assessment	Any analysis that predicts the behavior of a system or system component under a given set of constant and/or transient conditions. Performance assessments will include estimates of the effects of uncertainties in data and modeling.
Performance measure	A set of quantitative characteristics or properties that are related to an objective and designed to measure the extent to which the objective is achieved.
Permian Basin	A region in the Central United States where, during Permian time 280 to 225 million years ago, there were many shallow seas that laid down vast beds of salt and other evaporites. The Deaf Smith site is in the Permian Basin.
Population dose	The sum of the radiation doses received by the individual members of a population exposed to a particular source or event. It is expressed in units of man-rem.
Postclosure	The period of time after the closure of the geologic repository.
Post-waste-emplacement	After the authorization of repository construction by the NRC.
Potentially acceptable site	Any site at which, after geologic studies and field mapping but before detailed geologic data gathering, the DOE undertakes preliminary drilling and geophysical testing for the definition of site location.
Potentially adverse condition	A condition that is presumed to detract from expected system performance, but further evaluation, additional data, or the identification of compensating or mitigating factors may indicate that its effect on the expected system performance is acceptable.
Preclosure	The period of time before and during the closure of the geologic repository.
Pre-waste-emplacement	Before the authorization of repository construction by the NRC.
Qualifying condition	A condition that must be satisfied for a site to be considered acceptable with respect to a specific guideline.
Quaternary Period	The second period of the Cenozoic Era, following the Tertiary, beginning 2 to 3 million years ago and extending to the present.

Radioactive waste	High-level radioactive waste and other radioactive materials, including spent nuclear fuel, that are received for emplacement in a geologic repository.
Radionuclide retardation	The process or processes that cause the time required for a given radionuclide to move between two locations to be greater than the ground-water travel time, because of physical and chemical interactions between the radionuclide and the geohydrologic unit through which the radionuclide travels.
Rem	A unit dose of ionizing radiation that has the same biological effect as 1 roentgen of x-rays; 1 rem approximately equals 1 rad for x-, gamma, or beta radiation. Thus, a rem is a unit of individual dose that allows a comparison of the effects of various radiation types as well as quantities.
Repository	Synonym for "geologic repository".
Repository closure	This term is synonymous with "closure" (10 CFR Part 960, Subpart A).
Repository construction	All excavation and mining activities associated with the construction of shafts, shaft stations, rooms, and necessary openings in the underground facility, preparatory to radioactive-waste emplacement, as well as the construction of necessary surface facilities, but excluding site-characterization activities.
Repository horizon	The horizontal plane within the host rock where the location of the repository is planned.
Repository operation	All of the functions at the site leading to and involving radioactive-waste emplacement in the underground facility, including receiving, transportation, handling, emplacement, and, if necessary, retrieval.
Repository system	The geologic setting at the site, the waste package, and the repository, all acting together to contain and isolate the waste.
Restricted area	Any area access to which is controlled by the DOE for purpose of protecting individuals from exposure to radiation and radioactive materials before repository closure, but not including any areas used as residential quarters, although a separate room or rooms in a residential building may be set apart as a restricted area.

Retrieval	The act of intentionally removing radioactive waste before repository closure from the underground location at which the waste had been previously emplaced for disposal.
Risk averse	An attitude toward an uncertain adverse impact wherein a sure loss equal to the expected value of the uncertain impact is preferred to the uncertainty.
Risk neutral	An attitude toward an uncertain adverse impact wherein the uncertainty and a sure loss equal to the expected value of the uncertainty are equally undesirable.
Risk preferring	Synonym for "risk prone."
Risk prone	An attitude toward an uncertain adverse impact wherein the uncertainty is preferred to a sure loss equal to the expected value of the uncertain impact.
Salt	The common mineral sodium chloride (NaCl) and any impurities in it.
Salt dome	A diapiric or piercement structure with a central plug that has risen through the enclosing sediments from a deep mother bed of salt.
Saturated zone	That part of the earth's crust beneath the water table in which all voids, large and small, are ideally filled with water under pressure greater than atmospheric.
Scaling factor	A numerical parameter (usually between 0 and 1) used to scale component utilities in a multiattribute utility function. The magnitudes of scaling factors represent value tradeoffs among performance measures, and not the importance of those performance measures.
Scenario	A set of postulated conditions or sequence of processes and events that could affect the performance of a repository after closure.
Sensitivity analysis	A method used to identify the inputs to an analysis or model to which the results are most sensitive.
Significant source of ground water	(1) An aquifer that: (i) is saturated with water having less than 10,000 milligrams per liter of total dissolved solids; (ii) is within 2,500 feet of the land surface: (iii) has a transmissivity greater than 200 gallons per day per foot,

provided that any formation or part of a formation included within the source of ground water has a hydraulic conductivity greater than 2 gallons per day per square foot; and (iv) is capable of continuously yielding at least 10,000 gallons per day to a pumped or flowing well for a period of at least a year; or (2) an aquifer that provides the primary source of water for a community water system as of the effective date of 40 CFR Part 191, Subpart B.

Site — A potentially acceptable site or a candidate site, as appropriate, until such time as the controlled area has been established, at which time the site and the controlled area are the same.

Site characterization — Activities, whether in the laboratory or in the field, undertaken to establish the geologic conditions and the ranges of the parameters of a candidate site relevant to the location of a repository, including borings, surface excavations, excavations of exploratory shafts, limited subsurface lateral excavations and borings, and in situ testing needed to evaluate the suitability of a candidate site for the location of a repository, but not including preliminary borings and geophysical testing needed to assess whether site characterization should be undertaken.

Siting — The collection of exploration, testing, evaluation, and decision-making activities associated with the process of site screening, site nomination, site recommendation, and site approval for characterization or repository development.

Siting guidelines — Synonym for "guidelines."

Special source of ground water — Those Class I ground waters identified in accordance with the EPA's Ground-Water Protection Strategy published in August 1984 that: (1) Are within the controlled area encompassing a disposal system or are less than five kilometers beyond the controlled area; (2) are supplying drinking water for thousands of persons as of the date that the DOE chooses a location within that area for detailed characterization as a potential site for a disposal system (e.g., in accordance with Section 112(b)(1)(B) of the Act); and (3) are irreplaceable in that no reasonable alternative source of drinking water is available to that population.

Spent fuel	Synonym for "spent nuclear fuel."
Spent nuclear fuel	Fuel that has been withdrawn from a nuclear reactor following irradiation, the constituent elements of which have not been separated by reprocessing.
Surface facilities	Repository support facilities within the restricted area.
Surface water	Any waters on the surface of the Earth, including fresh and salt water, ice, and snow.
System	The geologic setting at the site, the waste package, and the repository, all acting together to contain and isolate the waste.
System performance	The complete behavior of a repository system in response to the conditions, processes, and events that may affect it.
Tectonic	Of, or pertaining to, the forces involved in, or the resulting structures or features of, "tectonics".
Tectonics	The branch of geology dealing with the broad architecture of the outer part of the Earth, that is, the regional assembling of structural or deformational features and the study of their mutual relations, origin, and historical evolution.
Tertiary	The earlier of the two geologic periods that make up the Cenozoic Era, extending from 65 million to 1.8 million years ago.
To the extent practicable	The degree to which an intended course of action is capable of being effected in a manner that is reasonable and feasible within a framework of constraints.
Tuff	A rock formed of compacted volcanic ash and dust.
Uncertainty	A situation where there are a number of possible outcomes and one does not know which of them has occurred or will occur.
Underground facility	The underground structure and the rock required for support, including mined openings and backfill materials, but excluding shafts, boreholes, and their seals.
Undisturbed performance	The predicted behavior of a disposal system, including consideration of the uncertainties in

predicted behavior, if the disposal system is not disrupted by human intrusion or the occurrence of unlikely natural events.

Unrestricted area	Any area that is not controlled for the protection of individuals from exposure to radiation and radioactive materials.
Unsaturated zone	The zone between the land surface and the water table. Generally, water in this zone is under less than atmospheric pressure, and some of the voids may contain air or other gases at atmospheric pressure. Beneath flooded areas or in perched water bodies, the water pressure locally may be greater than atmospheric.
Utile	Unit of utility.
Utility	A quantitative measure of preference or desirability.
Utility curve	Synonym for "utility function."
Utility function	A means for converting from the unit of evaluation used for consequences or impacts to the utility scale.
Value judgments	Intrinsic human values, either personal or societal, relevant to a decision.
Value tradeoff	An expression of the relative desirability of achieving improved performance against one objective or collection of objectives versus achieving improved performance against another objective or collection of objectives. Expressing a value tradeoff requires answering the following type of question: "How much of a decrease in performance measure 1 would be tolerated to obtain an increase in performance measure 2 of one unit?"
Waste	Synonym for "radioactive waste."
Waste form	The radioactive waste materials and any encapsulating or stabilizing matrix.
Waste package	The waste form and any containers, shielding, packaging, and other sorbent materials immediately surrounding an individual waste container.
Water table	That surface in a body of ground water at which the water pressure is atmospheric.
Weight	Synonym for "scaling factor."

Appendix A

PARTICIPANTS IN THE DECISION-AIDING METHODOLOGY

Appendix A

PARTICIPANTS IN THE DECISION-AIDING METHODOLOGY

This appendix identifies the participants in the development and application of the decision-aiding methodology to the evaluation of the nominated sites for characterization; it also describes in general terms their roles in the process. About 60 people, consisting of DOE staff and management, technical specialists from support contractors, and consultants, participated in the development and application of the methodology. The process began in the summer of 1985 and was completed in April 1986.

A general flow diagram showing the process for implementing the methodology is presented in Figure A-1. The participants are listed in Tables A-1 through A-4 together with their organizational affiliations, qualifications, and the roles they played in the development and application of the methodology.

A task force was established by the Office of Geologic Repositories (OGR) in the DOE's Office of Civilian Radioactive Waste Management (OCRWM) for overseeing, coordinating, and implementing the decision-aiding methodology, and a management plan for this purpose was developed. This task force consisted of a methodology lead group, groups of technical specialists with training and experience in the specialty disciplines represented in the siting guidelines, and OGR management. In addition to DOE staff, the technical specialists included employees of the OCRWM technical support contractor (Roy F. Weston, Inc.).

The methodology lead group was composed of one DOE employee, Mr. T. P. Longo, and three consultants: Dr. P. F. Gnirk, Dr. M. W. Merkhofer, and Dr. R. L. Keeney. The three consultants were selected because of their particular expertise or type of experience. Dr. Gnirk was selected because of his previous involvement in the development of the DOE siting guidelines and many years of technical experience in geologic disposal. Drs. Merkhofer and Keeney were selected because of their experience in applications of multiattribute utility theory to similar or related problems.

The methodology lead group was responsible for developing the logical basis for the application of the methodology, for guiding all participants through the required steps of the methodology, and for eliciting from the technical staff and management the technical and value judgments required as input information. In addition, the group was responsible for compiling and editing this evaluation report. The group was under the general oversight of the senior DOE managers identified in Table A-4, and it was assisted by a number of other key professional people, named in Table A-1.

The groups of technical specialists were composed of Federal employees, technical experts from the OCRWM technical support contractor, and consultants. They are organized by discipline in Tables A-2 and A-3; the responsibilities of the various groups are consistent with functional responsibilities and staff responsibilities for program execution within the OCRWM. They were responsible for developing, with guidance from the

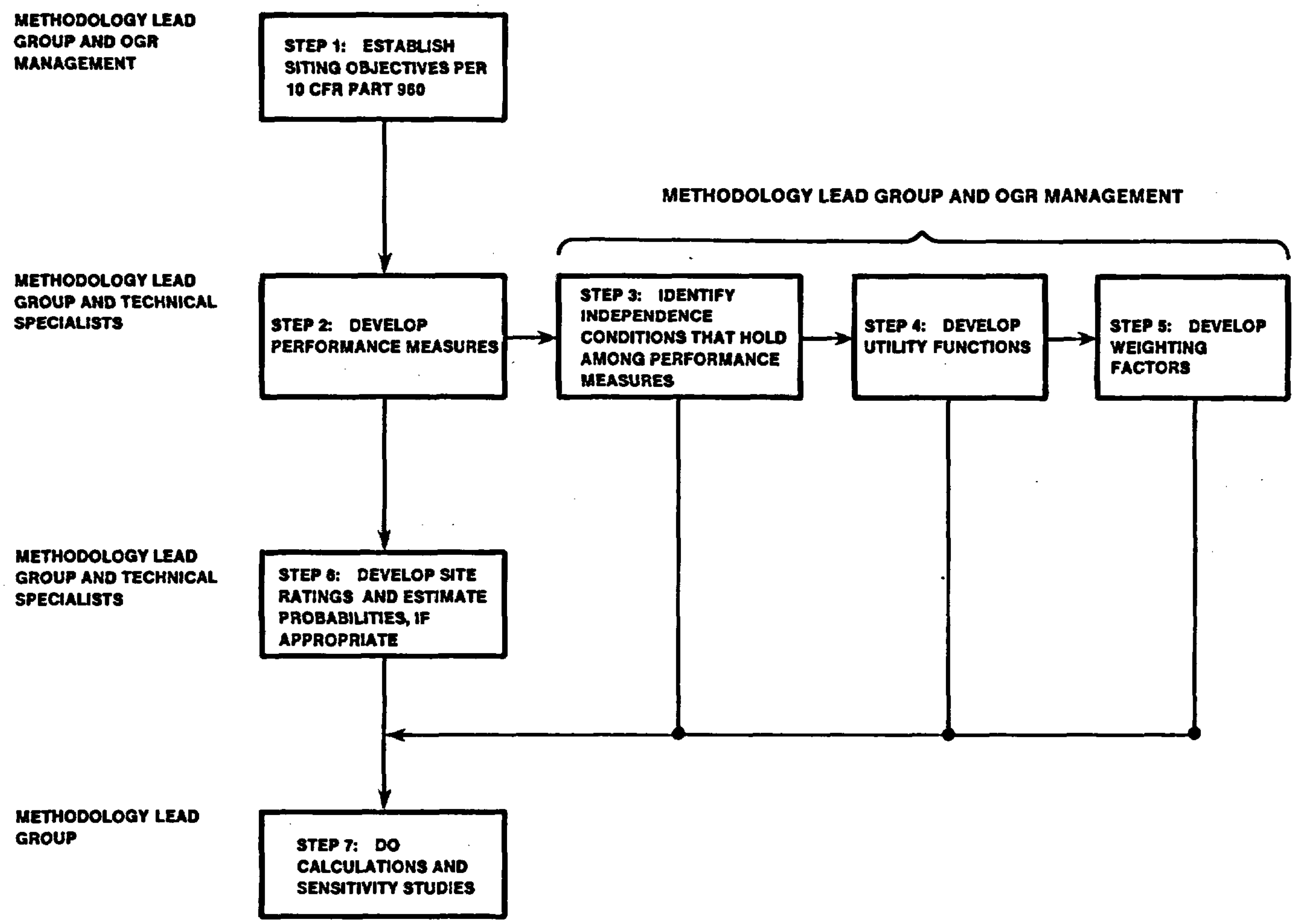

Figure A-1. General flow of activities and division of responsibilities for implementing the formal methodology.

methodology lead group, the influence diagrams and associated performance measures for the various siting objectives. They were also responsible for scoring the sites against the performance measures. An ad hoc technical advisory group, composed of technical specialists who were not directly involved with the development and implementation of the methodology, provided advice to the postclosure technical specialists on the development of the performance measures. Also listed in Table A-2, the members of this advisory group were selected because of their expertise in performance assessment.

Several OGR managers, listed in Table A-4, participated in those parts of the methodology that require value or policy judgments. These included, in particular, the specification of siting objectives, the verification of independence assumptions, and the specification of utility curves and weighting factors. In addition, the OGR managers reviewed the progress of the implementation of the methodology on a regular basis.

Table A-1. Participants in the development and application of the methodology

Name	Affiliation	Academic training	Areas of expertise and experience	Years of professional experience: Geologic disposal	Decision analysis	Other areas	Role[A]
METHODOLOGY LEAD GROUP							
T. P. Longo	DOE/OGR[B]	M.S. in geochemistry, University of Maryland (1979)	Repository siting, geosciences, DOE repository program	6		1	Lead; all steps
P. F. Gnirk	RE/SPEC Inc.	Ph.D. in rock mechanics, University of Minnesota (1966)	Rock mechanics, repository engineering, DOE siting guidelines	15		10	All steps
R. L. Keeney[C]	University of Southern California	Ph.D. in operations research, Massachusetts Institute of Technology (1969)	Decision analysis, risk analysis, siting energy facilities		15	5	All steps
M. W. Merkhofer	Applied Decision Analysis, Inc.	Ph.D. in engineering economic systems, Stanford University (1975)	Decision analysis, risk assessment, environmental analysis		14	3	All steps
KEY PERSONNEL SUPPORTING THE METHODOLOGY LEAD GROUP							
D. M. Murphy[C]	Applied Decision Analysis, Inc.	M.S. in engineering economic systems, Stanford University (1985)	Decision analysis		1	1	2, 6
E. Olmstead[D]	Independent	M.S. in engineering economic systems, Stanford University (1982)	Decision analysis		2	2	2
L. G. Shaw	Weston	Ph.D. in political science, West Virginia University (1982)	Institutional affairs and socioeconomic analysis	3		15	1, 2, 6
D. L. Siefken	Weston	M.S. in geology, University of Florida (1974)	Geohydrology, geotechnical engineering, 10 CFR Part 60	7		5	1, 2, 6

Table A-1. Participants in the development and application of the methodology (continued)

Name	Affiliation	Academic training	Areas of expertise and experience	Years of professional experience: Geologic disposal	Decision analysis	Other areas	Role[A]
KEY PERSONNEL SUPPORTING THE METHODOLOGY LEAD GROUP (continued)							
A. Sicherman	Lawrence Livermore National Laboratory	M.S. in operations research, Massachusetts Institute of Technology (1975)	Decision analysis, computer modeling		11	5	7
R. G. Schwartz	Applied Decision Analysis, Inc.	Ph.D. in engineering economic systems, Stanford University (1985)	Decision analysis		2	2	7

[A] The numbers in this column correspond to the steps in the methodology (Figure A-1) as follows: (1) establish siting objectives; (2) develop influence diagrams and performance measures; (3) identify independence conditions that hold among the performance measures; (4) develop utility functions; (5) develop weighting factors; (6) develop site ratings and estimate probabilities, if appropriate; and (7) perform calculations and sensitivity studies.

[B] Office of Geologic Repositories.

[C] Started January 17, 1986.

[D] Until January 1, 1986.

Table A-2. Postclosure technical specialists and their roles in the development and application of the methodology

Name	Affiliation[A]	Academic training	Areas of expertise and experience	Years of professional experience: Geologic disposal	Years of professional experience: Other areas	Role[B]
POSTCLOSURE TECHNICAL SPECIALISTS						
A. J. Jelacic	DOE/OGR	Ph.D. in geology, University of Rochester (1971)	Planning and management, geology	2	13	Lead: 1, 2, 6
J. E. Rhoderick	DOE/OGR	B.S. in geology, James Madison University (1977)	Engineering geology, licensing	7	1	2, 6
G. L. Faulkner	USGS--DOE/OGR	M.A. in geology, University of Wyoming (1950)	Hydrology, hydrogeology, petroleum geology	2	34	2, 6
K. S. Czyscinski	Weston	Ph.D. in geochemistry, University of South Carolina (1975)	Ground-water chemistry, waste-package performance assessment	7	4	2, 6
W. M. Hewitt	Weston	M.S. in nuclear engineering, Catholic University of America (1980)	Safety assessments, human interference, 10 CFR Part 60, DOE siting guidelines	10	8	2, 6
R. E. Jackson	Weston	Ph.D. in geology, University of North Carolina (1973)	Geotechnology, seismology, licensing	5	11	2, 6
J. K. Kimball	Weston	M.S. in geology (seismology), University of Michigan (1980)	Seismology, geophysical investigations, licensing	2	4	2, 6
S. V. Panno	Weston	M.S. in geology, Southern Illinois University (1978)	Ground-water chemistry, corrosion	5	5	2, 6
M. W. Pendleton	Weston	M.S. in geology, Rutgers University (1973)	Geology, hydrology, 10 CFR Part 60	5	8	2, 6

Table A-2. Postclosure technical specialists and their roles in development and application of the methodology (continued)

Name	Affiliation[A]	Academic training	Areas of expertise and experience	Years of professional experience: Geologic disposal	Years of professional experience: Other areas	Role[B]
			POSTCLOSURE TECHNICAL SPECIALISTS (continued)			
L. D. Rickertsen	Weston	Ph.D. in nuclear physics, Yale University (1972)	Repository performance assessment, numerical modeling	10	3	2, 6
D. L. Siefken	Weston	M.S. in geology, University of Florida (1974)	Geohydrology, geotechnical engineering, 10 CFR Part 60	7	5	1, 2, 6
			AD HOC TECHNICAL ADVISORY GROUP			
F. W. Bingham	Sandia National Laboratories	Ph.D. in nuclear physics, Indiana University (1962)	Performance assessment (salt, tuff)	10	14	1, 2
J. E. Campbell	Intera Technologies, Inc.	Ph.D. in physics, Virginia Polytechnic Institute (1969)	Performance assessment (salt)	10	7	1, 2
B. Sagar	Rockwell-Hanford Operations	Ph.D. in hydrology, University of Arizona (1973)	Performance assessment (basalt), numerical modeling, fluid mechanics	5	17	1, 2
W. D. Weart	Sandia National Laboratories	Ph.D. in geophysics, University of Wisconsin (1961)	Performance assessment (salt)	12	18	1, 2

[A] Acronyms: OGR, Office of Geologic Repositories; USGS, U.S. Geological Survey.
[B] The numbers in this column correspond to the steps in the methodology (Figure A-1) as follows: (1) establish siting objectives; (2) develop influence diagrams and performance measures; (3) identify independence conditions that hold among the performance measures; (4) develop utility functions; (5) develop weighting factors; (6) develop site ratings and estimate probabilities, if appropriate; and (7) perform calculations and sensitivity studies.

Table A-3. Preclosure technical specialists and their roles in development and application of the methodology

Name	Affiliation[A]	Academic training	Areas of expertise and experience	Years of professional experience: Geologic disposal	Years of professional experience: Other areas	Role[B]
			PRECLOSURE RADIOLOGICAL SAFETY			
R. S. Pelletier	DOE/ESH	B.S. in civil engineering, Merrimack College (1971)	Environmental protection, defense-waste management and disposal	5	10	Lead; 2, 6
V. W. Lowery	DOE/OGR	M.S. in physics, University of Akron (1968)	Nuclear engineering, repository design	3	14	2, 6
W. M. Hewitt	Weston	M.S. in nuclear engineering, Catholic University of America (1980)	Safety assessments, 10 CFR Part 60, DOE siting guidelines	10	8	2, 6
W. C. McClain	Weston	Ph.D. in mining engineering, University of Newcastle-Upon-Tyne (1963)	Repository engineering, rock mechanics, disposal and repository siting technology	22	0	2
G. Martin, Jr.	Weston	M.S. in nuclear engineering, Polytechnic Institute of New York (1976)	Radiological engineering, health physics	1	12	2, 6
L. G. Shaw	Weston	Ph.D. in political science, West Virginia University (1980)	Institutional affairs, socioeconomic analysis	3	15	2, 6
D. A. Waite	Battelle-ONWI	Ph.D. in general engineering, Oklahoma State University (1972)	Health physics, radiological assessment, waste management	8	12	2
			ENVIRONMENTAL QUALITY			
G. J. Parker	DOE/OGR	M.S. in engineering management, Catholic University of America (1982)	Environmental, regulatory, and siting activities	2	18	Lead; 1, 2, 6
R. K. Sharma	DOE/OGR	Ph.D. in ecology, Utah State University (1968)	Environmental assessments, regulatory compliance	2	23	2, 6
D. M. Valentine	DOE/OGR	J.D., Howard University (1975)	Legislation, commercial law, environmental specialty	0.5	9	6

Table A-3. Preclosure technical specialists and their roles in development and application of the methodology (continued)

Name	Affiliation[A]	Academic training	Areas of expertise and experience	Years of professional experience: Geologic disposal	Years of professional experience: Other areas	Role[B]
			ENVIRONMENTAL QUALITY (continued)			
C. E. Bradley	DOE/ESH	M.S. in regional planning, University of Pennsylvania (1975)	Environmental assessments, regulatory compliance	3	15	1, 2, 6
J. L. Friedman	Weston	Ph.D. in anthropology, Washington State University (1975)	Cultural resource management, environmental issues, archaeological issues	1	12	2, 6
D. E. Keough	Weston	B.S. in environmental resource management, Pennsylvania State University (1978)	Applied ecology, remedial environmental actions	3	4	2
B. L. Nichols	Science Applications, Inc.	B.S. in natural resources, University of Wisconsin (1964)	Environmental impact assessments, regulatory compliance, aquatic ecology	5	17	2
K. A. St. John	Weston	M.S. in environmental management, Duke University (1980)	Environmental impact assessments, environmental regulations	4	4	2, 6
R. L. Toft	Weston	M.S. in environmental management, Duke University (1977)	Environmental impact assessments, environmental regulations	3	7	2, 6
A. H. Vogel	Weston	B.S. in geology, Dickinson College (1983)	Environmental management, hazardous waste	0	3	6
			SOCIOECONOMICS			
B. G. Gale	DOE/OGR	Ph.D. in history and philosophy of science, University of Chicago (1970)	Socioeconomics, intergovernmental analysis, financial assistance programming	3	12	Lead; 1, 2, 6

Table A-3. Preclosure technical specialists and their roles in development and application of the methodology (continued)

Name	Affiliation[A]	Academic training	Areas of expertise and experience	Years of professional experience: Geologic disposal	Years of professional experience: Other areas	Role[B]
			SOCIOECONOMICS (continued)			
A. M. McDonough	DOE/OGR	B.S. in economics, University of Pennsylvania (1974)	Natural resource analysis, transportation, program management, economics	1	10	2, 6
C. G. Halloran	Weston	B.A. in history and public policy, Duke University (1983)	Socioeconomics, institutional analysis	3	-	2, 6
L. G. Shaw	Weston	Ph.D. in political science, West Virginia University (1982)	Institutional affairs, socioeconomic analysis	3	15	1, 2, 6
R. K. Travis	Weston	M.A. in economic geography, University of Pittsburgh (1974)	Socioeconomics	1	11	2, 6
			TRANSPORTATION			
E. L. Wilmot	DOE/OSTS	M.S. in ceramic engineering, nuclear materials, University of Washington (1972)	Transportation risk analysis, radiological protection, cask design	10	4	Lead; 1, 2, 6
L. S. Marks	DOE/OSTS	B.A. in chemistry, Queens College of City University of New York (1970)	Transportation risk analysis, statistical analysis	1	14	2, 6
P. A. Bolton	Weston	M.S. in biochemistry and microbiology, University of Connecticut (1960)	Radioactive-waste transportation, emergency response	3	15	2, 6
			EASE AND COST OF SITING, CONSTRUCTION, OPERATION, AND CLOSURE			
M. W. Frei	DOE/OGR	M.S. in nuclear engineering, University of Washington (1976)	Repository design and development, nuclear engineering	8	3	Lead; 2, 6

Table A-3. Preclosure technical specialists and their roles in development and application of methodology (continued)

Name	Affiliation[A]	Academic training	Areas of expertise and experience	Years of professional experience: Geologic disposal	Years of professional experience: Other areas	Role[B]
		EASE AND COST OF SITING, CONSTRUCTION, OPERATION, AND CLOSURE (continued)				
J. J. Fiore	DOE/OGR	M.S. in business administration, University of Maryland (1978)	Repository cost analysis, mechanical engineering	6	7	2, 6
S. P. Schneider	DOE/OGR	B.S. in chemical engineering, University of Maryland (1978)	Repository cost and design analysis, spent-fuel storage technology	6	2	2, 6
P. L. Collyer	ICF	M.S. in economic geology, Syracuse University (1971)	Mine engineering and design, mine safety	5	11	2
D. A. Gardner	Weston	M.S. in nuclear engineering, State University of New York (1970)	Repository design and cost analysis	2	16	2, 6
J. W. Nelson[C]	Weston	M.S. in civil engineering (geotechnical), Massachusetts Institute of Technology (1977)	Repository design engineering, rock mechanics	6	3	2, 6
G. W. Toth	Weston	B.S. in industrial engineering, Pennsylvania State University (1967)	Repository cost analysis, underground repository cost modeling	1	18	2

[A] Acronyms: ESH, Environment, Safety and Health; OGR, Office of Geologic Repositories; ONWI, Office of Nuclear Waste Isolation; OSTS, Office of Storage and Transportation Systems.

[B] The numbers in this column correspond to the steps in the methodology (Figure A-1) as follows: (1) establish siting objectives; (2) develop influence diagrams and performance measures; (3) identify independence conditions that hold among the performance measures; (4) develop utility functions; (5) develop weighting factors; (6) develop site ratings and estimate probabilities, if appropriate; and (7) perform calculations and sensitivity studies.

[C] Until January 31, 1986.

Table A-4. DOE/OCRWM Management and their roles in the development and application of the methodology

Name	Position and affiliation	Academic training	Areas of expertise and experience	Years of professional experience: DOE/OCRWM[A]	Other Federal agencies	Private industry	Role[B]
W. J. Purcell	Associate Director for the Office of Geologic Repositories, DOE/OCRWM	M.S. in mechanical engineering, Carnegie Mellon University (1949)	Project management, management of research and development, engineering design, nuclear engineering	1.5	3	38	1,3,4,5
T. H. Isaacs	Deputy Associate Director for the Office of Geologic Repositories, DOE/OCRWM	M.S. in engineering and applied physics, Harvard University (1971)	Waste-management policy, program management, nuclear engineering, fuel-cycle activities	2	16	1	1,3,4,5
E. S. Burton	Director, Siting Division, Office of Geologic Repositories, DOE/OCRWM	B.A. in mathematics, Amherst College (1951)	Waste management, environmental policy analysis, program management, facility siting, statistics	4	12	14	1,3,4,5
R. Stein	Director, Engineering and Geotechnology Division, Office of Geologic Repositories, DOE/OCRWM	B.S. in chemical engineering, University of Pittsburgh (1954)	Waste management, project management, nuclear engineering, repository engineering, siting and licensing	8	17	7	1,3,4,5

[A] Includes the DOE Office of Civilian Radioactive Waste Management and predecessor agencies that were responsible for the geologic disposal program before the Nuclear Waste Policy Act of 1982.

[B] The numbers in this column correspond to the steps in the methodology (Figure A-1) as follows: (1) establish siting objectives; (2) develop influence diagrams and performance measures; (3) identify independence conditions that hold among the performance measures; (4) develop utility functions; (5) develop weighting factors; (6) develop site ratings and estimate probabilities, if appropriate; and (7) perform calculations and sensitivity studies.

Appendix B

INFLUENCE DIAGRAM AND PERFORMANCE MEASURES FOR THE POSTCLOSURE OBJECTIVES

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Appendix B

INFLUENCE DIAGRAM AND PERFORMANCE MEASURES FOR THE POSTCLOSURE OBJECTIVES

B.1 INTRODUCTION

Chapter 3 briefly summarizes the influence diagram and performance measures for evaluating the long-term waste-isolation capabilities of the five nominated sites. This appendix provides additional detail on the influence diagram and the development of the performance measures. In addition, it illustrates the application of the performance-measure scales in three examples.

The overall objective for the postclosure period is to minimize adverse impacts on the health and safety of the public (see Figure B-1). Specifically, the objective is to minimize the number of radiological health effects experienced by the public and attributable to the repository. Directly related to this objective are the DOE siting guidelines of 10 CFR Part 960, Subpart C (DOE, 1984). For example, the postclosure system guideline specifies waste containment and isolation requirements based on the regulatory standards established by the Nuclear Regulatory Commission (NRC) and the Environmental Protection Agency (EPA) for the protection of the health and safety of the public in 10 CFR Part 60 and 40 CFR Part 191, respectively (NRC, 1983; EPA, 1985a). Each of the eight postclosure technical guidelines is related to the containment and isolation of the wastes for 10,000 years. In addition, the first three technical guidelines include conditions for the geohydrology, geochemistry, and rock characteristics of a site--that is, the natural barriers--that relate to the performance of a repository for up to 100,000 years.

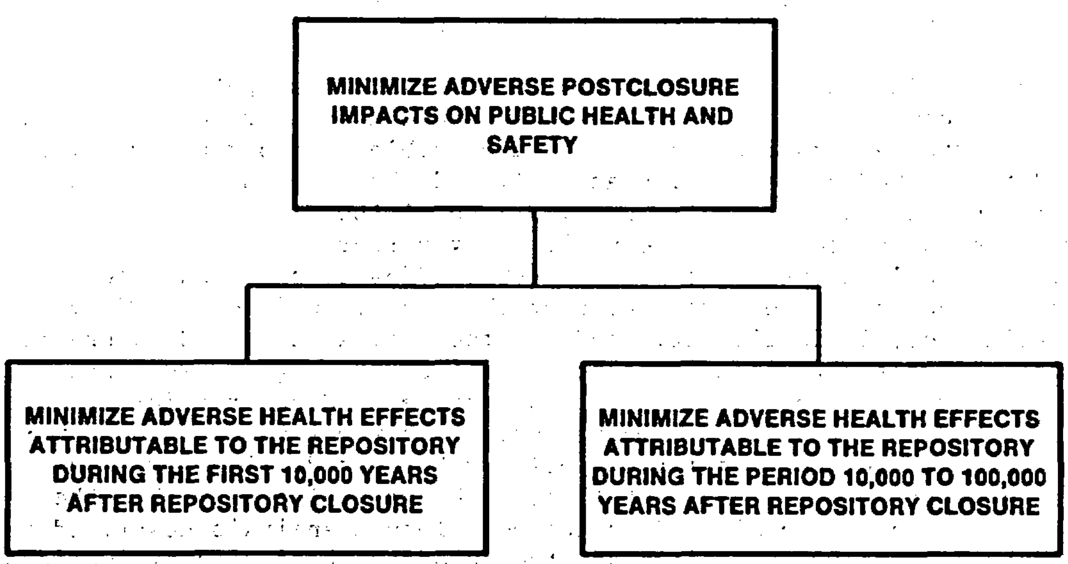

Figure B-1. Postclosure objectives hierarchy.

The overall postclosure objective is divided into two subobjectives that are defined as follows:

- Minimize the adverse health effects attributable to the repository during the first 10,000 years after closure.

- Minimize the adverse health effects attributable to the repository during the period 10,000 to 100,000 years after closure.

These two time periods allow independent judgments in two distinct time intervals that are considered in the postclosure guidelines of 10 CFR Part 960, Subpart C.

B.2 INFLUENCE DIAGRAM

To aid in the development of the postclosure performance measures, a detailed influence diagram was constructed (Figure B-2). This graphic device illustrates the influence of important site characteristics on the ability of a repository to meet the waste containment and isolation requirements specified in 10 CFR Part 60 and 40 CFR Part 191, Subpart B. The site characteristics have been numbered to facilitate their description in the text that follows. The characteristics that are believed to be the most important are shown as double ellipses.

The most important factors that affect the number of postclosure health effects are the number of people exposed (the population at risk (2)) and the radiation dose each person receives (3). Radiation doses are assumed to depend on radionuclide releases to the accessible environment and the transport, retardation, dispersion, accumulation, and uptake of the released radionuclides along a variety of environmental pathways. These pathways determine the doses received by people from ingestion, inhalation, or immersion and are the factors designated 19, 21, 22, 23, etc., in Figure B-2.

Although the ingestion, inhalation, and immersion dose pathways in the accessible environment are shown on the influence diagram for completeness, evaluations of the factors influencing the accessible environment over the next 10,000 to 100,000 years are impractical, and, because the estimated radionuclide releases are so small, a comparison of the sites against these factors was deemed unnecessary. The preliminary performance assessments reported in the environmental assessments (DOE, 1986a-e) show that the releases to the accessible environment over the next 10,000 to 100,000 years should be relatively insignificant. Indeed, the estimated ground-water-travel times indicate that the radionuclides released from the engineered-barrier system are not expected to reach the ground surface or discharge into surface-water bodies during this time period. Likely pathways to the biosphere would, therefore, consist of wells or borings drilled for water or for mineral exploration. For both of these pathways, releases within the controlled area have been evaluated in the postclosure analysis described here and in Chapter 3. The DOE therefore adopted an approach to site evaluations that is based on comparing the cumulative radionuclide releases to the accessible environment (23) against the EPA release limits—an approach

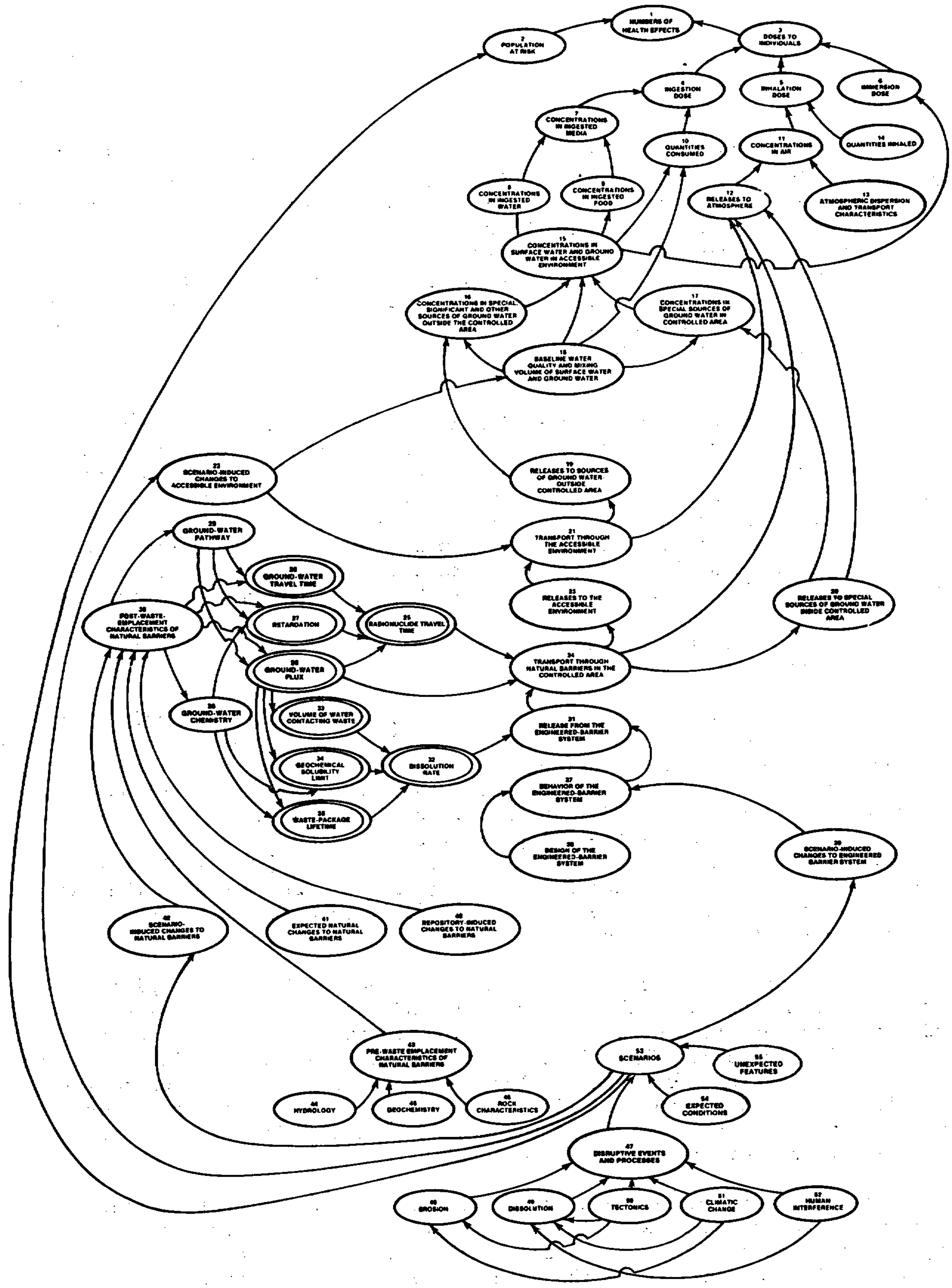

Figure B-2. Relationships among the factors influencing the numbers of postclosure health effects attributable to the repository.

that is consistent with the EPA and the NRC regulations. Accordingly, the DOE has not evaluated differences among the sites with respect to pathways to the biosphere within the accessible environment.

Factors 23, 24, 31, 37 and 38 in Figure B-2 represent a simplified illustration of the defense in depth provided by the multiple barriers of a geologic repository against releases of radionuclides to the accessible environment. The influence diagram shows that the releases to the accessible environment in the postclosure period (23) are largely determined, in the expected case, by the releases from the engineered-barrier system (31) and the transport of the radionuclides though the natural barriers in the controlled area (24). In some instances, there may be scenario-induced changes to the engineered-barrier system (39) or the natural-barrier system (42), and these changes would affect releases to the accessible environment.

The types and quantities of radionuclides transported and the period of time over which transport occurs depend chiefly on the radionuclide-travel time (25), the ground-water flux (28), and the geochemical conditions of the geohydrologic units in which transport occurs (27, 34, 36). The radionuclide-travel time may depend on the ground-water-travel time (26) if ground water is the principal transporting medium and on the processes that retard the movement of the dissolved radionuclides in relation to the movement of the ground water (27). Each of these factors is determined by the type and characteristics of the ground-water pathway (29) and the postclosure characteristics of the natural barriers (30) (e.g., hydraulic gradients, conductivity, effective porosity, and geochemistry).

The radionuclides transported through the natural barriers originate as releases from the engineered-barrier system (31). The types and quantities of radionuclides released from the engineered-barrier system are related to the behavior of the engineered-barrier system (37) and the rate of release for individual radionuclides (32). The behavior of the engineered-barrier system (e.g., the response to the thermal pulse introduced by the emplaced waste) is related to the design of the engineered-barrier system (38), such as waste-package spacing, and any changes in the engineered-barrier system that are induced by disruptive processes and events (39), such as the breach of waste packages by fault displacement.

The rate of release of a particular radionuclide from the engineered-barrier system depends on the volume of ground water in contact with the waste (33), the concentration of that radionuclide in that water (34), and the waste-package lifetime (35). The volume of ground water in contact with the waste is influenced by the ground-water flux, while the concentration of radionuclides and the waste-package lifetime are related to the ground-water temperature and chemistry, which, in turn, are influenced by the post-waste-emplacement characteristics of the natural barriers.

The post-waste-emplacement characteristics of the natural barriers are affected by the changes expected to occur in the natural barriers because of ongoing or expected geologic processes (e.g., the erosion of the land surface), repository-induced changes in the natural barriers (e.g., thermally induced uplift), pre-waste-emplacement characteristics (e.g., hydraulic gradients), and changes in the characteristics of the natural barriers induced by disruptive processes and events (factors 40, 41, 42, and 43).

The ability of a site to isolate waste from the accessible environment for thousands of years after repository closure is influenced by processes, events, and conditions that are both expected and unexpected. A postulated set of conditions and processes, or sequence of events, at a site is known as a scenario (53). For the purpose of comparing the nominated sites, three kinds of scenarios were developed: (1) a scenario for conditions, processes, and events that are expected at a site because of existing information (factor 54); (2) a scenario for unexpected features that may affect repository performance, including such things as undetected geologic structures and anomalies and unforeseen responses of the rock mass to the emplacement of heat-generating wastes (factor 55); and (3) scenarios that lead to the disruption of the expected repository behavior through natural processes and events or human interference (factor 47). It is intended that the scenarios reflect the favorable and potentially adverse conditions (10 CFR Part 960, Subpart C) identified at the sites in the final environmental assessments (DOE, 1986a-e).

The changes in the characteristics of the natural barriers that are induced by disruptive processes and events occurring any time during the first 10,000 years after closure are evaluated (as they affect releases from the engineered-barrier system or transport through natural barriers in the controlled area) for both the first 10,000 years and for the period 10,000 to 100,000 years after repository closure. Disruptive processes and events include tectonic activity (50), erosion (48), dissolution (49), and human interference (52). The rates of erosion or dissolution at a site may be affected by other processes, such as tectonic activity, climatic changes (51), or human interference.

Although some of the disruptive events may affect the size of the population at risk, this is not a discriminator among the sites because of the inability to project future population densities and distributions over the next 10,000 years. Accordingly, the relationship is shown on the influence diagram but was not used in the evaluation of sites.

B.3 PERFORMANCE MEASURES

B.3.1 BACKGROUND INFORMATION

The overall objective for the postclosure performance of a repository is to minimize adverse impacts on the health and safety of the public. As shown in Figure B-1, this objective is divided into two lower-level objectives that are stated in terms of minimizing adverse health effects in the public during two specific time periods after repository closure: during the first 10,000 years and from 10,000 to 100,000 years. Health effects were used in the risk assessment conducted by the EPA to establish the environmental standards for geologic disposal under 40 CFR Part 191, Subpart B. The health effects of concern are the cancer deaths that could result from exposure to the radionuclides released from the repository to the accessible environment. Genetic effects that could result from exposure to these radionuclides were also considered by the EPA, but the results of detailed evaluations led to the conclusion that genetic effects are not likely to be significant in comparison with somatic effects.

The primary-containment requirements of the EPA standards for the post-closure system, as embodied principally in Table 1 of Appendix A of 40 CFR Part 191, specify the allowable cumulative releases of radionuclides to the accessible environment per 1000 metric tons of uranium (MTHM) for the first 10,000 years after repository closure. These release limits were developed by the EPA after evaluations of the expected performance of geologic repositories in generic basalt, granite, salt, and tuff formations, assuming (1) very general models of environmental transport; (2) a linear, nonthreshold dose-effect relationship between radiation exposure and premature deaths from cancer; and, (3) current population distributions and death rates. For each 1000 MTHM, the allowable cumulative release limits specified by the EPA represent the potential for approximately 10 cancer deaths in 10,000 years. Because of the assumption of a linear dose-effect relationship between radiation exposure and deaths from cancer, releases are in effect proportional to health effects, and the former can be taken as a useful surrogate for the latter.

The EPA specifies in 40 CFR Part 191, Subpart B, that, for the first 10,000 years after closure, the releases to the accessible environment must not exceed the limits given in Table 1 of Appendix A of that regulation. The EPA chose this time period partly because compliance with quantitative standards for a substantially longer period would entail projections of releases that reflect considerably more uncertainty. Furthermore, it was felt that a repository system capable of meeting the containment requirements for 10,000 years would continue to protect people and the environment well beyond 10,000 years. On the other hand, the DOE siting guidelines (10 CFR 960.3-1-5) require the sites being considered for development as a repository to be compared in terms of the projected releases from an undisturbed repository over 100,000 years. The DOE therefore chose to evaluate site performance under expected conditions for two time periods: for scenarios involving unexpected features and disruptive processes and events during the first 10,000 years and during the period 10,000 to 100,000 years after closure. However, evaluations of repository performance were carried out for both time periods only if the scenario was judged likely to occur during the first 10,000 years (i.e., with a probability greater than 1 chance in 10,000); that is, the consequences of such scenarios were not evaluated if they were postulated to occur after the first 10,000 years. The effect of relaxing this assumption on the postclosure analysis was examined in a sensitivity analysis (see Figure 3-14).

Additional postclosure objectives and associated performance measures were considered. For example, objectives could have been developed in terms of the individual protection requirements (40 CFR 191.15) and the ground-water protection requirements (40 CFR 191.16) of the EPA standards because of their relationship to health effects. However, it was not practical to do so because the bounding analyses presented in Section 6.4.2 of the environmental assessments (EAs) for the nominated sites (DOE, 1986a-e) provide no basis for discrimination among sites. That is, these analyses indicate no impacts on individuals or ground water during the first 1000 years at any of the sites for undisturbed performance of the repository because no releases to special or significant sources of water are expected. Because of the inability to discriminate among sites on this basis, objectives related to special or significant sources of ground water were not included in the objectives hierarchy. Similarly, postclosure performance measures were not developed in terms of the characteristics of the accessible environment, such as future human populations or environmental pathways, because predictions of such conditions for 10,000 years are not reliable.

B.3.2 PERFORMANCE-MEASURE SCALES

The performance measures are defined in terms of radionuclide releases as follows:

- The cumulative release of radionuclides to the accessible environment during the first 10,000 years after repository closure.

- The cumulative release of radionuclides to the accessible environment during the period 10,000 to 100,000 years after repository closure.

The scale of each of these performance measures is defined in terms of the release limits specified as the containment requirements by Table 1 of Appendix A of 40 CFR Part 191. These requirements specify the allowable cumulative releases of individual radionuclides to the accessible environment for the first 10,000 years after repository closure in terms of curies per 1000 MTHM. These requirements also specify the way in which these individual release limits are to be combined to define an overall system release limit. The scales for the performance measures are expressed in terms of this release limit, as shown in Figures B-3 and B-4. The scale for the first performance measure is chosen to range between 0 and 10, where a score of 10 corresponds to a cumulative release of 0.0001 of the release limit and a score of 0 corresponds to 10 times the release limit. The evaluations in Section 6.4.2 of the EAs suggested that the expected releases to the accessible environment at all nominated sites may be so low that a linear scale in terms of releases may not provide sufficient discrimination among the sites. Therefore, a logarithmic scale in terms of multiples of the EPA release limits was chosen; that is, a score of 0 corresponds to 10 times the EPA release limits, a score of 2 corresponds to the EPA release limits, a score of 4 corresponds to 0.1 of the limits, and so forth.

The scale for the second measure (10,000 years to 100,000 years) is analogous to the scale for the first measure except that now a score of 0 corresponds to 100 times the EPA release limits for the first 10,000 years, a score of 2 corresponds to 10 times the limits, and so forth. Therefore, the scale increments in releases for this 90,000-year period are 10 times those for the first 10,000 years.

Also shown on the right of Figures B-3 and B-4 are the site characteristics for which the radionuclide releases specified on the left are judged to be reasonably equivalent. As shown in the influence diagram of Figure B-2, the site characteristics important to the determination of releases include the ground-water-travel time, the ground-water flux, the solubility of key radionuclides, and retardation factors for key radionuclides. There are many combinations of such characteristics that could lead to an equivalent release or score. For example, the release from a site with a long ground-water-travel time may be the same as that from a site with a very low solubility of key radionuclides. These sites, in turn, may be equivalent to another site that has both a moderate ground-water-travel time and a moderate retardation of radionuclide movement in relation to the ground-water velocity.

It is possible to aggregate these site characteristics in terms of the way they affect releases from the engineered-barrier system and transport through the natural barriers by means of two performance factors:

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	Scale	Characteristics of the Site for Which the Cumulative Releases on the Left Are Judged To Be Reasonable
0.0001	10 9	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	8 7	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	6 5	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	4 3	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	2 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	0	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. Equivalent combinations of performance factors are given in Table B-1.

Figure B-3. Scale used to aid the judgmental estimation of releases during the first 10,000 years after repository closure.

PERFORMANCE MEASURE—Cumulative Releases of Radionuclides to the Accessible Environment During the Time Period 10,000 to 100,000 Years After Repository Closure

Cumulative Releases Over the First 10,000 Years as Multiples of the EPA Release Limits	Scale	Characteristics of the Site for Which the Cumulative Releases on the Left Are Judged To Be Reasonable
0.001	10	The characteristics and conditions at the site are such that, during the period 10,000 to 100,000 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 90,000 years is about 10 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.
	9	• The median travel time to the accessible environment of any key radionuclide is about 300,000 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	8	The characteristics and conditions at the site are such that, during the period 10,000 to 100,000 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 90,000 years is about 30 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.
	7	• The median travel time to the accessible environment of any key radionuclide is about 250,000 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.
0.1	6	The characteristics and conditions at the site are such that, during the period 10,000 to 100,000 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 90,000 years is about 100 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.
	5	• The median travel time to the accessible environment of any key radionuclide is about 200,000 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.
1	4	The characteristics and conditions at the site are such that, during the period 10,000 to 100,000 years after closure, radionuclide releases to the accessible environment are small. This judgment is based on a combination of site characteristics that implies some 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 90,000 years is about 300 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.
	3	• The median travel time to the accessible environment of any key radionuclide is about 150,000 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.
10	2	The characteristics and conditions at the site are such that, during the period 10,000 to 100,000 years after closure, radionuclide releases to the accessible environment are significant. This judgment is based on a combination of site characteristics that implies a 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 90,000 years is about 1000 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.
	1	• The median travel time to the accessible environment of any key radionuclide is about 100,000 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.
100	0	The characteristics and conditions at the site are such that, during the period 10,000 to 100,000 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 90,000 years is about 10,000 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 about 10,000 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. Equivalent combinations of performance factors are given in Table B-2.

Figure B-4. Scale used to aid the judgmental estimation of releases occurring during the period 10,000 to 100,000 years after repository closure.

- A factor for release from the engineered-barrier system, F, which is a measure of the amount of radionuclides that can be expected to be dissolved into the ground water during the period of interest.

- A factor for transport through the natural barriers, T_i, which is a measure of the travel time of key radionuclides through the natural barriers to the accessible environment under post-waste-emplacement conditions.

The first performance factor, F, would be given by the sum of the ratios of the cumulative releases to the accessible environment to the EPA release limits if these cumulative releases were predicted in a performance analysis. For direct-release scenarios, F could be estimated by considering the quantity of the total radionuclide inventory that is released in terms of the EPA release limits. For indirect-release scenarios, in which the radionuclides are dissolved into ground water that moves to the accessible environment, F can be estimated from a simple relationship that depends on the ability of the ground water to dissolve the waste. In this case, F is approximated by the sum of the ratios of the maximum quantities of radionuclides dissolved during the period of interest to the quantities allowable under the EPA release limits:

$$F = \sum_i QC_i/RL_i,$$

where

Q = total volume of ground water (cubic meters per 1000 MTHM) that will be in contact with the waste during the period of interest

C_i = the maximum concentration of each radionuclide (curies per cubic meter of ground water) based on solubility, inventory, or other factors

RL_i = the release limit for each radionuclide (curies per 1000 MTHM) as specified in Table 1 of Appendix A of 40 CFR Part 191

In general, the performance factor F depends on two site characteristics:

1. Ground-water flow through or across the host rock.

2. The chemical conditions of the ground water insofar as they may relate to its capability to dissolve radionuclides.

As an example of the dependence of F on the ground-water flow through the host rock, the following can be considered: for a host rock characterized by a constant, uniform ground-water flux, the term Q can be estimated from

$$Q = fAt,$$

where

f = ground-water flux (cubic meters per square meter per year)

A = effective cross-sectional area (square meters per 1000 MTHM) through which the ground water flows

t = period of interest (years)

It is the total volume of ground water available for the dissolution of waste that is of interest here. The volume of water that is in contact with the waste also depends on the pathways to and around the waste package. With regard to the dependence of F on the site geochemistry, C_i can be estimated from the isotopic solubilities, S_i, of the radionuclides and waste-form constituents in the ground water at a site, taking into account the expected repository conditions (e.g., temperature and controlling phases).

The second performance factor, T_i, is the travel time of the i^{th} key radionuclide from the engineered-barrier system to the accessible environment under post-waste-emplacement conditions. A key radionuclide is defined as one that contributes significantly to the quantity of radionuclides that could be dissolved in the ground water during the period of interest (e.g., more than 1 percent of the quantity F above). An example of the way T_i can be estimated is given by the expression

$$T_i = R_i T,$$

where R_i is the retardation factor (dimensionless) for a key radionuclide and T is the travel time (years) of the ground water from the engineered-barrier system to the accessible environment under post-waste-emplacement conditions. For other transport mechanisms, such as diffusion, T_i would be estimated on the basis of other factors.

In general, the travel time of any key radionuclide depends on (1) the chemical and physical properties of the rock insofar as they may relate to the capability to retard the migration of radionuclides, and (2) the mechanism of radionuclide transport through the natural barriers under post-waste-emplacement conditions.

The two performance factors F and T_i offer a simple and direct way, though approximate, to relate site characteristics to estimates of releases to the accessible environment. For example, if the characteristics of the ground water flowing through the repository result in a value of 0.01 for the parameter F during the first 10,000 years, the cumulative release to the accessible environment can be estimated conservatively to be about 1 percent of the EPA release limits (assuming that ground water is the only transport medium). Similarly, if a substantial fraction (say 90 percent) of the pathways through the natural barriers have radionuclide-travel times longer than 10,000 years, then only a fraction (10 percent in this example) of the radionuclide inventory can possibly reach the accessible environment during 10,000 years.

When the two performance factors are considered together, the estimated releases for a site may be lower than those obtained by considering each factor individually. For example, in the first case considered above, F may be found to have a value of 0.01 because of favorable geochemical and ground-water-flux conditions. This value corresponds to 1 percent of the EPA release limits. Furthermore, suppose that the ground-water-travel time and the radionuclide-retardation characteristics are such that only 10 percent of the radionuclides released from the engineered-barrier system can reach the accessible environment in 10,000 years. Then the actual release to the accessible environment would be less than 0.1 percent of the EPA release limits.

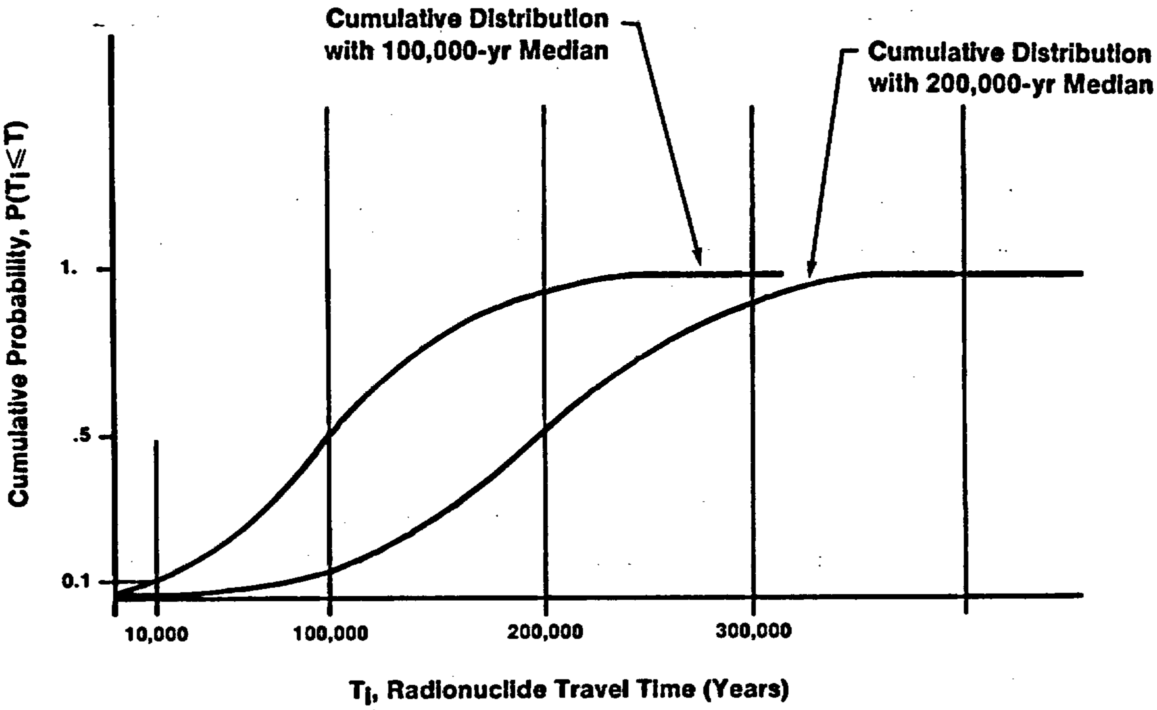

Figure B-5. Illustration of relationship between median radionuclide travel time and fraction of released radionuclides reaching accessible environment.

The actual distribution of the travel times required to quantify T_i is a site-specific factor that is not easily estimated before site characterization. However, the total distribution need not be known in detail in order to determine the effect on releases. For example, as illustrated in Figure B-5, the important information is the portion of travel paths with travel times of less than 10,000 or 100,000 years. A conservative analysis could indicate that the travel-time distribution has such characteristics that, if the median travel time is 100,000 years, about 10 percent of the radionuclides released from the engineered-barrier system would reach the accessible environment in 10,000 years (and 50 percent in 100,000 years).

Similarly, if the median travel time is 200,000 years, then about 1 percent of the radionuclides released from the engineered-barrier system would be released to the accessible environment in 10,000 years and about 10 percent in 100,000 years. Furthermore, for each additional 100,000 years of travel time, the fraction of radionuclides released to the accessible environment in the specified period decreases by an order of magnitude. The actual distribution may provide a smaller fraction of the pathways with travel times of less than 10,000 years or 100,000 years; however, these assumptions are considered to provide a reasonable and conservative basis for the evaluation of releases.

Table B-1. Scores for the first performance measure on the basis of cumulative releases for the first 10,000 years after repository closure

T_1 (median travel time of key radionuclides to accessible environment) (years)	F (fraction of radionuclides dissolved in ground water during the first 10,000 years as multiple of EPA release limits)										
	10	3.2	1	0.32	0.1	0.03	0.01	0.003	0.001	0.0003	0.0001
0	0	1	2	3	4	5	6	7	8	9	10
50,000	1	2	3	4	5	6	7	8	9	10	
100,000	2	3	4	5	6	7	8	9	10		
150,000	3	4	5	6	7	8	9	10			
200,000	4	5	6	7	8	9	10				
250,000	5	6	7	8	9	10					
300,000	6	7	8	9	10						
350,000	7	8	9	10							
400,000	8	9	10								
450,000	9	10									
500,000	10										

There are many combinations of F and T_1 that, together, result in equivalent system performance with respect to releases to the accessible environment over a given time period. Examples of such combinations are given in Tables B-1 and B-2 for the two performance measures. For example, in the case of a site in which F is equal to 0.01 over 10,000 years because of a moderate quantity of ground-water flow past the waste and favorable solubility limits, the associated score for that performance measure is at least 6, regardless of the radionuclide-travel time at the site. If, in addition, the median value of T_1 is 100,000 years, the fraction of the dissolved radionuclides reaching the accessible environment is assumed to be about 10 percent; therefore, the release to the accessible environment would correspond to 0.001 of the EPA release limits. Therefore, the site would receive a score of at least 8. A site with the above characteristics is essentially equivalent to another site with F equal to 0.1 and a median value of T_1 equal to 200,000 years. The potential tenfold increase in the dissolution of waste is compensated for by a longer median radionuclide-travel time. Since the release to the accessible environment would be about 0.001 of the release limits, this site would also receive a score of about 8.

The performance factors F and T_1 were developed for the purpose of estimating repository performance on the basis of available information for the important characteristics of a site. To this point, the performance of the engineered-barrier system has not been addressed. Impacts of site characteristics on the engineered-barrier system can be taken into account most conveniently by considering the waste-package lifetime. In estimating F, the quantity of radionuclides dissolved in the ground water during the first 10,000 years will be affected by the length of time that the disposal container remains intact or by the quantity of water remaining for waste dissolution after the container-corrosion process is substantially complete. Likewise, the time delay before radionuclides reach the accessible environment depends on container lifetime and the time of radionuclide travel through the controlled zone. Thus, for site evaluations against the performance measures, estimates of F and T_i can be revised by expert judgment to reflect the potential benefits of the waste package in restricting radionuclide releases.

Careful judgment must be exercised in applying Tables B-1 and B-2 to obtain site scores from site characteristics. For example, the distributions used in the preliminary evaluations of travel time in Chapter 6 of the EAs are consistent with the assumptions given here; however, it is entirely possible that the actual travel-time distributions vary appreciably from those obtained with the assumed models of ground-water flow. It is certainly possible that releases estimated by using F and the median value of T_i may be underestimated or overestimated by a factor of 10 or more. Nevertheless, in spite of this uncertainty, this approach provides a useful association between site characteristics (right-hand side) and radionuclide releases (left-hand side) on the performance-measure scales.

Table B-2. Scores for the second performance measure on the basis of cumulative releases between 10,000 and 100,000 years after repository closure

T_i (median travel time of key radionuclides to accessible environment) (years)	F (fraction of radionuclides dissolved in ground water in 100,000 years as multiple of 10,000-year EPA release limits)										
	100	32	10	3.2	1	0.32	0.1	0.32	0.01	0.003	0.001
0 to 10,000	0	1	2	3	4	5	6	7	8	9	10
50,000	0	1	2	3	4	5	6	7	8	9	10
100,000	0	1	2	3	4	5	6	7	8	9	10
150,000	1	2	3	4	5	6	7	8	9	10	
200,000	2	3	4	5	6	7	8	9	10		
250,000	3	4	5	6	7	8	9	10			
300,000	4	5	6	7	8	9	10				
350,000	5	6	7	8	9	10					
400,000	6	7	8	9	10						
450,000	7	8	9	10							
500,000	8	9	10								
550,000	9	10									
600,000	10										

There are two additional points concerning the use of Tables B-1 and B-2 that should be mentioned. First, the performance factor T_1 used in estimating a score in the tables is the median travel time for key radionuclides. Estimates of ranges in the score should therefore be based not on the range of travel times but on the range of <u>median</u> values that could result from alternative conceptual models and conditions. Second, for scenarios leading to direct releases to the accessible environment, such as human intrusion or volcanism, the use of the left-hand scale of a performance measure may be the most appropriate approach to arrive at a score, rather than the use of surrogate measures like F and T_1. In such cases, Tables B-1 and B-2 would not be used.

B.3.3 EXAMPLE APPLICATIONS OF THE PERFORMANCE MEASURES

To demonstrate the use of the performance measures in site evaluations, this section presents three examples: (1) the generic sites used by the EPA in the development of 40 CFR Part 191, Subpart B; (2) a hypothetical repository in the Carrizo sandstone aquifer of south Texas; and (3) the five nominated sites in relation to the performance-assessment results for each.

The examples are included to address comments by the Board on Radioactive Waste Management of the National Academy of Sciences on portions of this report submitted for review on March 17, 1986. In particular, the Board made two recommendations. First, it suggested that the DOE show the postclosure results that would be obtained with the methodology for a repository at a site with poor geohydrologic characteristics. Second, the Board recommended that the DOE compare results obtained with the methodology against results calculated for generically similar sites considered by the EPA in the development of its final standards and against results calculated with performance-assessment models.

<u>Example 1: generic sites considered by the EPA</u>

The first example is the set of cases considered by the EPA in developing the containment requirements of 40 CFR Part 191, Subpart B. Specific cases for hypothetical repository systems in generic basalt, bedded-salt, tuff, and granite sites are described in the background-information document for the final EPA rule (EPA, 1985b). Using specified site characteristics and repository descriptions, cumulative releases to the accessible environment during the first 10,000 years after closure were calculated with the REPRISK code (Smith et al., 1982). In addition, relationships between predicted releases and associated health effects were used to help determine the release limits specified by Table 1 of Appendix A of 40 CFR Part 191.

The EPA did not evaluate releases for the period 10,000 to 100,000 years after closure, and therefore only the first performance measure is considered here. Table B-3 summarizes the application of the performance measure to the the four generic sites. The first row gives the health effects and the second row gives the cumulative releases leading to these health effects, as computed by the EPA. The third row gives the scores that would be assigned to each of these cases by directly relating the calculated cumulative releases to the left-hand side of the performance measure in Figure B-3.

The scores given in Table B-3 could be used to compare these generic sites if the model predictions were adequate to address site performance, including the uncertainties in conceptual models and site parameters. Premature reliance on such model predictions can be avoided by scoring the sites against the right-hand side of the performance measure of Figure B-3. The site parameters (F and T_i) required for this evaluation are given in the fourth and the fifth rows of Table B-3. These parameters were derived from the characteristics for the generic cases specified by the EPA (1985b). The scores associated with these parameters, as estimated from Table B-1, are given in the sixth row of Table B-3.

Comparison of the scores obtained by the two approaches shows that, for the four generic sites, scores based on the parameters F and T_i provide a

Table B-3. Performance-measure scores for EPA generic sites[a]

Parameter	Basalt	Bedded salt	Tuff	Granite
	SCORES OBTAINED BY EPA METHOD			
Health effects[b]	97	0	0	180
Cumulative release[c]	0.15	0	0	0.32
Score based on the left-hand side of Figure B-3[d]	4	10	10	3
	SCORES OBTAINED BY DOE METHOD			
F value[e]	0.6	0	0.6	0.6
T_i value[e] (years)	1.1×10^5	2.5×10^6	2×10^6	5×10^3
Score based on the right-hand side of the performance measure for first 10,000 years[f]	4-5	10	10	2-3

[a]Examples from the background-information document for the EPA final rule (EPA, 1985b, Table 8.10-1)
[b]Predicted premature deaths from cancer in 10,000 years for 100,000 MTHM.
[c]Multiple of the EPA release limits computed from Table 7.8-3 of the EPA background-information document (EPA, 1985b).
[d]Estimated from the predicted releases and the left-hand side of Figure B-3.
[e]Based on the characteristics of the generic sites considered by the EPA (EPA, 1985b).
[f]Estimated from Table B-1 and the right-hand side of the Figure B-3.

reasonably conservative measure of performance in terms of predicted releases. Although the generic sites are described in extremely simple terms, relying on one-dimensional effective-parameter representations for the elements of the system, the comparison provides some confidence that the performance measure can be useful in evaluating real sites.

Example 2: Carrizo sandstone aquifer of south Texas

The second example pertains to an actual geologic formation, a formation believed to be geologically unsuitable for a repository: the Carrizo sandstone aquifer of south Texas. Because of its importance as a water supply, this formation has been intensely studied for over 50 years (Klempt, Duffin, and Elder, 1976). Furthermore, trace concentrations of carbon-14, uranium-234, and uranium-238 in the ground water have been investigated for the validation of predictive models to be used in the evaluation of geologic repositories (Andrews and Pearson, 1984), and much of the information needed to apply the performance measure is available.

For the purpose of an illustrative example only, a hypothetical repository is assumed to be sited in the Carrizo sandstone formation. Hydrologic and geochemical data from the analysis by Andrews and Pearson (1984) are summarized in Table B-4. These same data were used to derive the F and T_i factors. To compute F, it was assumed that the dissolution of radionuclides into the moving ground water is controlled by the solubility of the uranium dioxide ceramic waste form. It was further assumed that the effective cross-sectional area for 1000 MTHM of spent fuel emplaced in the repository is 10,000 m^2. The applicable radionuclide inventories are given in Table 3.3.8 of an earlier DOE document (DOE, 1979).

Values for the performance factors F and T_i are given in Table B-4. The value of F ranges from 0.2 to 2000. If the key radionuclides are retarded very little, such as for carbon-14, the estimated release to the accessible environment would range from 0.2 to 2000 times the overall release limits of the EPA standards. If the transport velocity of the key radionuclides is similar to that of uranium, then the estimated releases would range from 0.02 to about 1000 times the overall release limits. For a release of 0.02 times the EPA limits, the Carrizo aquifer would score between 5 and 6 on the performance mea-

Table B-4. Parameters used in the evaluation of the Carrizo sandstone aquifer[a]

Hydrologic parameters	
Darcy velocity (m/hr)	0.6 to 1.0
Effective porosity	0.3 to 0.4
Ground-water velocity (m/yr)	1.5 to 3.3
Geochemical parameters	
Solubility of uranium (g/m^3)	10^{-6} to 10^{-3}
Retardation factor	
Carbon-14	1
Uranium	20 to 30
Performance parameters	
F	0.2 to 2000
T_i (years)	
Carbon-14	2000 to 3000
Uranium	30,000 to 100,000

[a] From Andrews and Pearson (1984).

sure for the first 10,000 years, according to Figure B-3 and Table B-1. Conversely, a release of 1000 times the EPA limits would give a score of -4 by extrapolation of Figure B-3 and Table B-1. If this latter situation were indeed the case, the Carrizo aquifer would be clearly unacceptable for a geologic repository.

Example 3: Nominated sites in relation to performance-assessment results

The third example involves the performance assessments used to evaluate the suitability of the nominated sites in Section 6.4.2 of the EAs (DOE, 1986a-e). These assessments yielded predictions of radionuclide releases on the basis of preliminary conceptual models and available data for the site characteristics and conditions. The models have not been validated and represent varying levels of development. The applications have ranged from bounding analyses to more-detailed evaluations that exclude the effects of the heat emitted by the waste. The results are useful for indicating the general trends to be expected at particular sites, but are not adequate for detailed and meaningful comparisons between and among sites. In part, the purpose of considering the performance-assessment results for the nominated sites as an example is to compare the scores obtained from the performance measure for 10,000 years against those obtained for the generic sites evaluated by the EPA.

Two separate cases were considered in Section 6.4.2 of the EA for each site. One case is referred to as the "performance-limits" case, in which all waste packages are assumed to fail at 300 years and the fractional rate of release from the engineered-barrier system is specified as one part in 100,000 per year. Thus, this case is analogous to the simple generic case evaluated by the EPA and presented in Table B-3. The results for the nominated sites are summarized in Table B-5 for both the first 10,000 years and for the period 10,000 to 100,000 years. These results suggest that the releases are expected to be generally smaller than those for the EPA generic sites and the scores are expected to be correspondingly higher.

This trend is also observed for the second case evaluated in the EAs. The second case (referred to as the "nominal" case) does not arbitrarily specify engineered-system performance, but takes into account the expected impacts of site characteristics and conditions on the engineered-barrier system. The releases predicted for this case are given in Table B-6. These values suggest that, indeed, the performance-measure scores for the nominated sites are expected to be high, with very small releases projected on the basis of the available information. It is to be noted that the nominal case considered in the evaluations in Appendix D is somewhat more general than the nominal case considered in Section 6.4.2 of the EAs and in Table B-6 and takes into account a wider range of uncertainty in site characteristics, conditions, and conceptual models than does Section 6.4.2 of the EAs. Thus, it is possible that scores for the site evaluations in Appendix D may range to values lower than those shown in Table B-6.

Summary remarks

There are some important features of the scoring evaluations that can be identified from the results of these examples. First, a site characteristic that is used to estimate the score is the median time of ground-water travel.

Table B-5. Predicted releases and corresponding performance-measure scores for the performance-limits case for nominated sites

Period	Performance measure	Davis Canyon	Deaf Smith	Richton Dome	Hanford	Yucca Mt.
10,000 years	Release[a]	0	0	0	0	<0.0002
	Score[b]	10	10	10	10	10
10,000-100,000 years	Release[a]	0	0	0	0.32[c]	0.035
	Score[b]	10	10	10	5	7

[a]Releases expressed as multiples of the EPA release limits in 40 CFR Part 191, Subpart B.

[b]Scores estimated from the performance measures of Figures B-1 and B-2.

[c]The environmental assessment for the Hanford site (DOE, 1986c) reports distributions of releases. The median value is shown in this table. The high value (95% confidence level) is 1.2 for the first 10,000 years and 1.0 for the period 10,000 to 100,000 years. The corresponding scores are 2 and 4, respectively. The low value (95% confidence level) is zero in each case.

Table B-6. Releases predicted for the nominal case in the environmental assessment[a] and corresponding performance-measure scores

Period	Performance measure	Davis Canyon	Deaf Smith	Richton Dome	Hanford	Yucca Mt.
10,000 years	Release[b]	0	0	0	0[d]	$<10^{-7}$
	Score[c]	10	10	10	10	10
10,000-100,000 years	Release[b]	0	0	0	0.29[d]	1.8×10^{-7}
	Score[c]	10	10	10	5	10

[a] See Section 6.4.2 of the environmental assessment for each site (DOE, 1986a-e).

[b]Releases expressed as multiples of the EPA release limits (Table 1 of Appendix A of 40 CFR Part 191).

[c]Scores estimated from the performance measures of Figures B-1 and B-2.

[d]The environmental assessment for the Hanford site (DOE, 1986c) reports distri-
butions of releases. The median value is shown in this table. The high value (95% confidence level) is 0.045 for the first 10,000 years and 0.45 for the period 10,000 to 100,000 years. The corresponding score is 5 in each case. The low value (95% confidence level) is zero in each case.

The EPA calculations, for example, are purely deterministic and do not take into account the distribution in travel time because of spatial variations in parameters and other factors that are expected for real sites.

The performance measure takes into account the fact that there may be travel times substantially shorter than the median value. In particular, because some radionuclides may be released before 10,000 years even if the median value is much greater than 10,000 years, use of the performance factors will generally provide lower scores (greater cumulative releases) than those resulting from deterministic calculations based on mean parameter values. This explains, in part, why in Table B-3 the scores based on the performance measure are in some cases lower than those based on the EPA calculations of radionuclide releases. In the evaluations of real sites, the median travel times should be used rather than the full range of travel times. Ranges in scores may result, however, if there are ranges in these median values resulting from different conceptual models or site conditions.

The second point is that the scoring methodology can accommodate more complex travel paths than those described in the simple cases considered by the EPA (1985b). In addition, it is not necessary to use the overly conservative approximation applied for the REPRISK calculations--that is, the volume of water that dissolves radionuclides is the entire volumetric flow crossing the host rock within the confines of the repository in 10,000 years. Only a fraction of this volume may be taken into account in the determination of the Q values required to calculate F. For example, it may be appropriate to consider only the water that is in contact with the waste package or the flux that intercepts an effective cross-sectional area containing the waste package. In the scoring of real sites, an effective area of about 30 m^2 per package was used.

Finally, there are cases in which it may be more appropriate to use the left-hand side of the performance measure rather than the right-hand side. For example, in scenarios involving direct releases of radionuclides, like those initiated by human intrusion or volcanic activity, the releases themselves can be evaluated directly (i.e., in terms of the fraction of the repository or package inventory that is released as a result of the disruption) and used to derive a score. In such cases, Tables B-1 and B-2 would not be used.

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Appendix C

DEVELOPMENT AND DESCRIPTION OF POSTCLOSURE SCENARIOS

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Appendix C

DEVELOPMENT AND DESCRIPTION OF POSTCLOSURE SCENARIOS

C.1 INTRODUCTION

This appendix describes the potentially significant scenarios that could lead to releases of radionuclides to the accessible environments at the various nominated sites. The scenarios are based, in general, on the known and expected characteristics of the sites and their geologic settings, as well as the generic features and conditions of the host-rock types and repository systems under consideration in this comparative evaluation. Initially, a broad collection of scenarios was identified, using information from the literature and the environmental assessments (EAs) for the nominated sites. By means of a screening process, the number of scenarios was gradually reduced to a credible set. In this process, particular attention was given to any scenarios that reflected in whole or in part any potentially adverse conditions identified at the sites. The criteria for the removal of a scenario from the initial collection were as follows:

- The impact of the postulated set of conditions and processes or sequence of events on the expected repository performance is such that the expected releases to the accessible environment are not increased by more than ten percent; or

- The likelihood of occurrence of a postulated set of conditions and processes or sequence of events is less than one chance in 10,000 over the first 10,000 years after repository closure.

Because of the manner in which the performance measures relate site characteristics to releases, the first criterion is reflective of significant changes in site characteristics (e.g., total volume of ground water in contact with the waste) and performance factors (e.g., radionuclide travel time) that are important to releases from the engineered-barrier system and transport through the natural barriers. The second criterion is based on guidance for implementation of 40 CFR Part 191, Subpart B, as specified in Appendix B of that regulation.

These criteria were applied first to specific processes and events and then to scenarios involving site-specific factors and information. To ensure that low-probability scenarios producing very large effects were not screened out, the product of the probability of the scenario and the factor by which it was estimated to increase risk was calculated. In no case was this product found to be significant for a scenario that was screened out.

Three different classes of scenarios were considered:

- Nominal case (expected conditions)
- Unexpected features
- Disruptive processes and events

The nominal case is based on the expected geohydrologic, geochemical, and rock conditions. The natural variability in these characteristics and the range of uncertainty that presently exists are taken into account. In addition, these conditions include natural changes that are expected at the sites. For example, the influence of expected climatic changes over the next 100,000 years on the geohydrologic system is considered. The influence of the excavation and the effect of the heat generated by the emplaced waste on the thermal, fluid, and chemical conditions are also considered.

The second class of scenarios includes the effects of unexpected features at the site. These features are not expected to be present, but they cannot be completely ruled out on the basis of the site information that is presently available. For example, an unexpected degree of subsidence or thermal expansion of the rock mass above the underground facility or geologic features that have not been detected (e.g., undetected breccia zones or undetected faults) could lead to extreme impacts on the expected performance of the repository.

The third class of scenarios includes processes and events that could lead to a disruption of the repository during the next 10,000 years. The potentially disruptive processes and events considered here include those related to erosion, dissolution, tectonic activity (including magmatic activity), and human interference. (As mentioned above, climatic changes are included as part of the nominal-case scenario (expected conditions).) Premature failures of the waste packages and the shaft and repository seals are also considered in this class of scenarios.

The probabilities of the three classes of scenarios are illustrated in Figure C-1. This figure shows the hypothetical probability distribution function for cumulative releases, y, at a typical site. The distribution of values is a result of variations in site characteristics, uncertainties in conditions, and the effects of disruptive processes and events. This distribution function is resolved into two components in Figure C-1. The first component, shown in the upper curve, represents the effects of expected conditions and the effects of unexpected features and accounts for most of the probability distribution. The division between expected conditions and unexpected features is shown as y_{max} in the figure. The portion of the first component ranging from $y = 0$ to $y = y_{max}$ is designated the nominal case. The total cumulative probability of the range is P_N. The remainder of the first component, representing the unexpected features, has a total probability of P_U.

The second component, shown in the lower curve, includes the effects of disruptive processes and events. The distribution for the second component has a total probability of P_D corresponding to the sum of the probabilities of the two disruptive-event scenarios in this example--that is, $P_{D1} + P_{D2}$. The total probability is

$$P_N + P_U + P_D = 1.$$

Since P_U, P_{D1}, and P_{D2} can be estimated on the basis of expert opinion, the probability of the nominal-case scenario is simply

$$P_N = 1 - P_U - P_D.$$

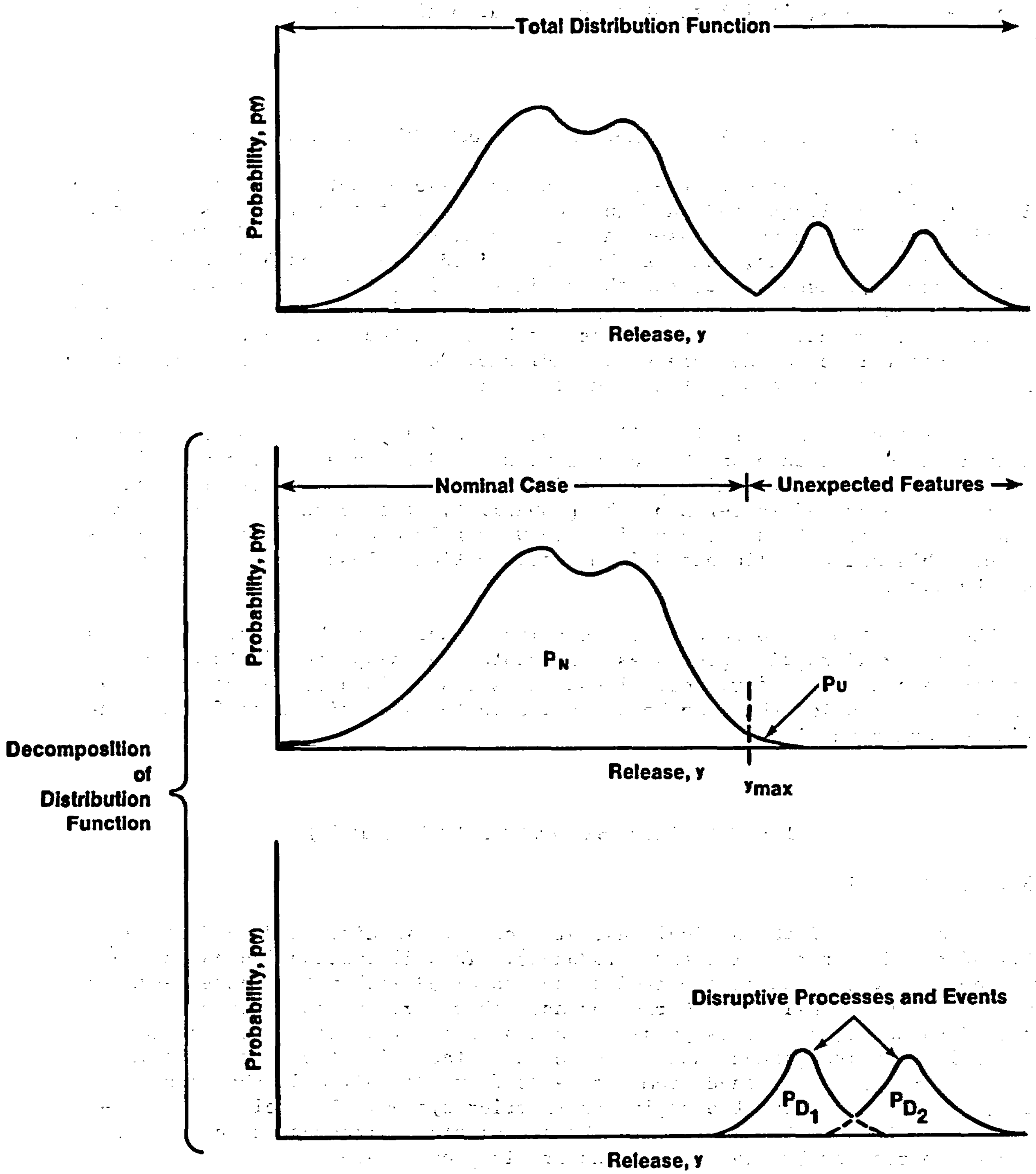

Figure C-1. Decomposition of the consequence probability distribution function.

This representation of the risk curve for a particular site is admittedly schematic; nevertheless, it illustrates the scenario classes described in more detail later.

C.2 APPROACH TO THE SCREENING AND DEVELOPMENT OF SCENARIOS

The general approach to the screening and development of the scenarios for this analysis is illustrated in Figure C-2. The first step is to establish the nominal case. This case is based on the current understanding of site characteristics and conditions, such as those described in Sections 6.3 and 6.4 of the environmental assessments for the nominated sites (DOE, 1986a-e), and takes into account the changes that are expected to occur in these conditions because of waste emplacement. The nominal case is based on the site factors and conditions that relate to the release of radionuclides from the engineered-barrier system and transport through the natural barriers.

The next step is to review all of the potentially disruptive processes and events induced by nature and humans and unexpected features that could affect site performance. A preliminary screening of these processes, events, and features is conducted in terms of the probability of occurrence. Those with a probability of less than 1 chance in 10,000 over 10,000 years are not considered credible and are eliminated from consideration unless the consequences could be large.

The next step is to construct scenarios in terms of the specific effects of potentially disruptive processes and events and unexpected features on expected repository performance. These steps result in a set of potentially significant scenarios that can be evaluated in terms of site-specific characteristics and conditions.

C.3 NOMINAL CASE (EXPECTED CONDITIONS)

C.3.1 INTRODUCTION

The analysis of the nominal case at each site is discussed in Section 6.4.2 of the EA for the site (DOE, 1986a-e). This discussion indicates, for example, that the waste is expected to be contained within the waste packages emplaced in the repository. Corrosion and other degradation processes are expected to occur, and it is possible that at some time the waste packages will fail, allowing ground water to come in contact with the waste. Radionuclides can then be leached from the waste form, dissolved in the ground water, and released from the engineered-barrier system. The released radionuclides can then be transported to the accessible environment by diffusion through the rock or by advective transport in ground water.

Under these conditions, the performance factors that are important include the amount of waste that can be dissolved into the ground water and the time of radionuclide travel through the natural barriers. The waste-package lifetime could also be important if it is comparable to, or greater than, the radionuclide-travel time. More-detailed understanding of the site

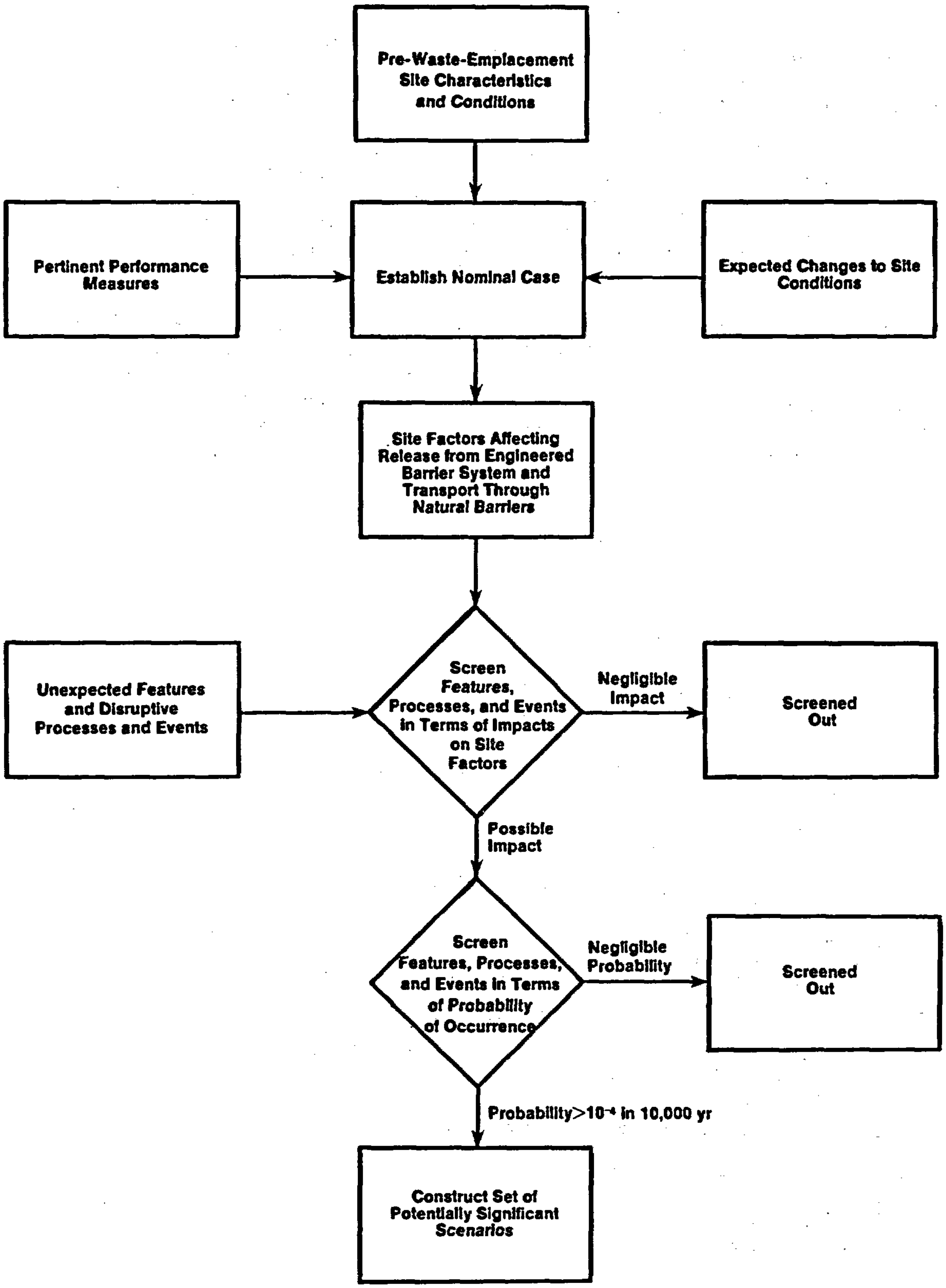

Figure C-2. General steps in the screening and development of scenarios.

after characterization could reveal that there are other important factors; however, on the basis of what is now known about each site, these two factors are considered to be the most important under expected conditions.

The specific conditions and site characteristics affecting the performance factors in the nominal case are summarized in Table C-1. These include the expected thermal, mechanical, geohydrologic, geochemical, and other conditions resulting from the pre-waste-emplacement characteristics of the site, the natural changes in these characteristics, and the changes induced by the excavation of the repository and the emplacement of heat-generating wastes.

For example, waste-package containment depends on the thermal, mechanical, fluid, chemical, and radiation conditions in the repository. Local thermal conditions affect waste-package degradation rates and local chemical and fluid conditions. Local temperatures depend, in turn, on the natural thermal environments at the site and the temperature increases resulting from waste emplacement. The important parameters that determine these conditions include

Table C-1. Site conditions and characteristics affecting repository-performance factors

1. <u>Conditions affecting waste-package lifetime</u>

   a. Thermal conditions
   b. Mechanical conditions (thermomechanical stresses, ground movement)
   c. Volume of, and replacement rate for, fluids near waste package
   d. Corrosion rate

2. <u>Local fluid conditions affecting the rate of release from the engineered-barrier system</u>

   a. Ground-water flux through the host rock or seepage into repository
   b. Number of packages exposed to water

3. <u>Local chemical conditions affecting the rate of release from the engineered-barrier system</u>

   a. Radionuclide solubility
   b. Waste-form dissolution rate
   c. Thermal effects on leach rates and local chemical conditions

4. <u>Conditions affecting ground-water movement to accessible environment</u>

   a. Rock characteristics that determine ground-water pathways
   b. Hydraulic properties
   c. Head gradients
   d. Unsaturated flow characteristics
   e. Constraints due to regional flow conditions

5. <u>Conditions affecting retardation</u>

   a. Sorption
   b. Precipitation
   c. Physical retardation
   d. Dispersion

6. <u>Other conditions affecting radionuclide-travel time</u>

   a. Diffusion transport
   b. Transport of gases

the thermal properties of the rock and the density of the waste in the repository. Likewise, the performance of the waste package is affected by local mechanical conditions, including the stresses imposed on the package by the rock. These conditions depend on the natural state of stress in the rock before excavation and the changes in the stresses in the rock induced by repository excavation and the heat generated by the waste. Similarly, the fluid and chemical conditions can affect the rate at which waste-package components corrode.

The release of radionuclides from the engineered-barrier system is also affected by local site conditions. For example, the waste-dissolution rate depends directly on the amount of water in contact with the waste, which depends on both the local flux through the repository and the amount of waste actually exposed to the water. If natural conditions or engineered barriers restrict the amount of ground water that can actually come in contact with the waste, effects on the dissolution of waste may be limited. The fluid conditions are determined by the natural flux of ground water through the host rock, the pathways created by the excavation of the repository, and the effects of local thermal conditions on the flow.

Local chemical conditions will also influence the degree of waste dissolution. The key geochemical parameters include those that control the amount of radionuclides that can be dissolved in the ground water and the rate of waste-form dissolution. These depend in turn on the solubility of the waste matrix and interactions between the waste form and the ground water.

The principal conditions affecting the transport of radionuclides through the geohydrologic system are the movement of ground water to the accessible environment and the retardation of the radionuclides in relation to the ground-water flow. The movement of the ground water depends on the existing pathways for the water (e.g., through fractures and joints or through the porous rock matrix), hydraulic properties (e.g., hydraulic conductivity and effective porosity), and the local head gradients. The movement of water within the controlled area is also determined by the regional pressure distribution and by the ability of surrounding geohydrologic units to receive and transmit water. Finally, flow conditions within the controlled area may be influenced by the heat generated by the waste. For sites in which ground-water flow in the unsaturated zone is important, water content or rock-matrix characteristics are also important. In either unsaturated or saturated flow, the key parameters for this evaluation include the ground-water-travel time and the flux of water along ground-water pathways.

The retardation of radionuclides is controlled by chemical and physical processes. Chemical retardation results from the sorptive characteristics of the minerals along ground-water pathways. In addition, radionuclides may precipitate from the ground water during transport through the natural barriers. Matrix diffusion and other physical processes also contribute to the retardation of radionuclides during transport. The dispersion of radionuclides in the ground water can occur because of molecular diffusion during transport, variations in hydrologic properties over the transport pathway, and other effects. Finally, factors other than advective transport can contribute to radionuclide-travel time. For example, in aquitards (beds with little or no measurable movement of water), transport by diffusion could be more important than advection. For volatile elements like krypton and iodine, vapor-phase transport could be significant.

The nominal case also depends on (1) the design and the expected behavior of the waste package and engineered-barrier system and (2) expected climate changes. These factors are considered below.

C.3.2 EXPECTED BEHAVIOR OF WASTE PACKAGES

Failure of most of the waste packages is not expected to occur for at least 1000 years at all sites. However, some packages may be flawed or may be damaged during the operational period. Other packages could be emplaced improperly so that they are subjected to conditions different from the design basis. Corrosion rates could be higher than those considered in preliminary projections based on short-term tests and estimates based on a uniform corrosion model. The evaluations for the nominal case in the EAs have included wide corrosion-rate ranges that take into account the range of uncertainty in this regard. Therefore, early failure of a small fraction of the waste packages cannot be precluded. As reported in Section 6.4.2 of the EAs (DOE, 1986a-e), analyses based on the assumption of early failure for some of the waste packages have also been conducted.

C.3.3 EXPECTED BEHAVIOR OF SHAFT AND REPOSITORY SEALS

The function of the seals is to limit the intrusion of water into the underground openings and restrict the migration of radionuclides along preferential paths created by the openings or the shafts. Leakage through the seals would not necessarily be significant if it is comparable to, or less than, the seepage expected to occur through the undisturbed rock. The analyses in the EAs have considered a wide range of hydraulic properties of the rock in their evaluation of expected conditions; for example, variations of several orders of magnitude have been considered in accounting for the heterogeneity of the rock. The properties expected for the seals are expected to fall well within these ranges. Therefore, ranges in the performance of the seal system are implicitly taken into account in the nominal case.

C.3.4 EXPECTED CLIMATIC CHANGES

Worldwide climatic changes are expected over the next 100,000 years. For example, minor variations in the earth's orbit have led to past changes in the seasonal distribution of solar insolation and appear to have initiated glacial cycles. It is believed that, over the next 23,000 years, perturbations from orbital variations may lead to a cooler climate with a trend toward enlarged continental ice sheets (Imbrie and Imbrie, 1980). This current cooling trend could produce a period of maximum glaciation in about 45,000 to 60,000 years (Craig et al., 1983; Spaulding, 1983). A minor glacial stage may occur about 15,000 to 23,000 years from now (Craig et al., 1983; Spaulding, 1983).

Glaciation could conceivably be important for waste isolation. For example, renewed continental glaciation could affect the repository if the stress state of the rock is affected by loading and unloading as the ice sheet advances and recedes over the site. If an ice sheet advanced to the recharge or drainage basins of the sites, the deep ground-water system might be affected. For one site, the Hanford site, such effects were evaluated in Section 6.3.1 of the EA (DOE, 1986d). Even taking into account impacts on erosion and recharge, it was concluded that the effects would be insignificant. At the other sites, glaciation is not likely to occur. It is generally accepted that the ice cover from renewed glaciation in the next 100,000 years will be confined to the regions that were covered with ice during the Pleistocene. Since none of these sites was glaciated during the Pleistocene, direct cover of any of the sites is not likely in the next 100,000 years.

A more important effect of climatic change could be attendant changes in rainfall. For example, increased precipitation during a future pluvial period could result in increased infiltration and recharge. These changes may decrease the time of ground-water travel to the accessible environment or increase the flux through the repository. At a repository in the unsaturated zone, an increase in the elevation of the water table, which could result from the increased recharge, could affect the travel time of ground water and the radionuclides dissolved in this water. Increased flux in the unsaturated zone could also be a factor affecting the travel time. New flow paths or modes of flow may result. Retardation may be affected if the flow is diverted to paths with different retardation characteristics. At the salt sites, salt-dissolution rates may be increased because of increased infiltration. The specific effects of a worldwide climatic change are clearly related to the unique geo- graphic features of each site.

A warming trend in the next 10,000 years from increases in atmospheric carbon dioxide could affect precipitation rates at the sites. Modeling predictions of long-term (100,000-year) climatic changes do not account for man-induced effects or the effects of volcanic activity on climatic cycles. However, the impact of such perturbations on the gradual cooling trend of the last 6000 years is not expected to overwhelm the long-term trend toward renewed glaciation and increased rainfall (see, for example, Craig et al., 1983; Imbrie and Imbrie, 1980).

The effects of worldwide climatic changes on the expected conditions that are considered in the nominal case include a potential increase in infiltration and recharge at the sites during a period commencing about 15,000 years after the present. Precipitation can increase by as much as 100 percent during a pluvial period (Spaulding, 1983), and the expected conditions necessarily take into account changes of this order.

C.4 UNEXPECTED FEATURES

C.4.1 INTRODUCTION

The nominal case is based on expected ranges of geohydrologic and geochemical conditions and rock characteristics. It is possible that extreme conditions outside these ranges could arise from the existence of features or characteristics which are not expected at the site but which cannot be unequivocally precluded by the present data. For example, extreme conditions could result from--

- A significant loss of rock-mass integrity because of excavation or the heat generated by the emplaced waste.

- Geologic features not detected at the nominated site.

- Other geohydrologic or geochemical changes in the site or of its response to the heat generated by the emplaced waste.

Extreme responses to repository excavation or waste emplacement include the subsidence or uplift of the rock mass above the underground repository. Extreme subsidence, for example, could cause a disturbance in the rock that could extend from the repository to an overlying aquifer and create preferential pathways for the incursion of water into the repository horizon and for the migration of radionuclides away from the repository.

Undetected geologic features includes those which may be present in similar rock formations elsewhere, but for which no evidence of their existence at the nominated sites has been obtained. The current information regarding the site may not be adequate to rule out such a feature unequivocally. It is possible that some features at the site will not be detected even during site characterization or during repository operation. Indeed, it is not expected that every geologic feature of the site will be characterized. Table C-2 lists some of the features that have been found in rock types like those at the nominated sites and may go undetected. These are described more fully below.

Table C-2. Unexpected features

Rock	Feature
Bedded salt	Small-scale folding Zones of increased porosity Brine pockets Pressurized gas pockets Lateral facies changes Breccia zones Fractures in brittle beds Small-scale faulting
Dome salt	Small-scale folding Zones of increased porosity Brine pockets Pressurized gas pockets Vertical, discontinuous nonsalt features Variations in salt quality
Basalt	Feeder dikes Profuse internal structures Flow pinchout Vertical fracture zones less than 1 meter wide Major fault
Tuff	Minor fault zones (less than 1 meter wide) Significant lateral variations Dikes and sills Vertical heterogeneity

C.4.2 SALT FORMATIONS

Unexpected features common to bedded and dome salt include small-scale folding, zones of increased porosity, brine pockets, and gas pockets. Small-scale folding can result in a significant variation in thickness and elevation, and it can occur over short distances. Because these variations may occur over short distances, they may not be determined from the vertical boreholes at a site. Brine pockets include both large inclusions of water that sometimes occur in the margins of salt domes and in other salt units and the large-scale zones of increased porosity that are saturated with brine and are sometimes associated with folding in salt beds. Gas pockets are zones of increased porosity that have been found in both bedded-salt and dome-salt structures.

Other undetected features that could occur at bedded-salt sites include lateral facies changes, breccia zones, fractures in brittle beds, and small-scale faulting. A lateral facies change can result from the pinching out of strata. Breccia zones are zones of rubble associated with small-scale internal dissolution. Fractures in brittle beds are potential connections across aquicludes or small-scale interbeds that could allow significant amounts of water to reach salt formations. Small-scale faulting refers to faults through the salt formations that, because of inhomogeneities in the salt, are not healed.

In salt domes there can exist vertical, discontinuous, nonsalt features or anomalous zones that separate the lobes of salt. Similarly, variations in the quality of the salt across a dome have been observed.

C.4.3 BASALT FORMATIONS

The possible undetected features at a basalt site include feeder dikes, profuse internal structure within the basalt flows, flow variations and pinchouts, extensive vertical fracture zones, or an undetected major fault. Feeder dikes are the channels through the basalt that provide the source for an overlying basalt flow. Profuse internal structures in a flow can include vesicular zones, spiracle zones, pillow zones, or other anomalous zones. Flow pinchouts are basalt-flow terminations. Vertical fracture zones are fractures that are not detected but could lead to conditions not taken into account under the expected conditions. Similarly, a major fault is one that cuts across many formations, is not detected by site characterization, and could be a significant pathway to the accessible environment.

C.4.4 TUFF FORMATIONS

The possible undetected features in tuff include minor fault zones, significant lateral variations in strata, dikes and sills, and vertical heterogeneity. Although faults are already known at the site, it is conceivable that there could be undiscovered faults that may have a significant impact on expected performance. Likewise, there may be variations within the tuff units--for example, in thickness and extent or in the presence of lithophysal cavities.

Intrusive structures like dikes or sills could be undetected. There may be vertical variations in properties that could lead, for example, to perched-water zones and could affect expected repository performance.

C.4.5 OTHER UNKNOWN FEATURES

Beyond the features that have not been identified at the nominated sites but are known to exist in similar rock formations elsewhere, there may be other features that are not known or suspected. For example, there could be features that have not yet been considered for the site because of insufficient information. In addition, there may be features that have not yet been considered to be important at any site because there is no experience with the behavior of a repository in deep geologic formations. The potential for such features adds uncertainty to the performance predictions. The factors that could be affected by such unexpected features are listed in Table C-3.

Table C-3. Potential impacts of unexpected features on the predictability of repository performance

ROCK CHARACTERISTICS
Dramatic differences in heat conduction in comparison with expected conditions
Dramatic differences in mechanical strength and deformation
GEOHYDROLOGY
Differences in ground-water flow mechanisms in comparison with expected conditions
Dramatic differences in ground-water flow paths
Dramatic differences in hydrologic properties (e.g., permeability, effective porosity)
Dramatic differences in head gradients
GEOCHEMISTRY
Dramatic differences in geochemistry from temperature increases much greater than those expected
Dramatic differences in ground-water geochemistry from new water source
Dramatic differences in the rate and the degree of low-grade metamorphism in rock and backfill
Dramatic departure from thermodynamic equilibrium

Dramatic differences in rock characteristics, such as differences in the thermal or mechanical-strength properties, could give rise to temperatures that are much higher than expected or to an unexpected loss of rock integrity. These phenomena could result in changes in the geohydrologic and geochemical conditions. Large differences in the geohydrologic and geochemical conditions could have important impacts on some performance factors at the site, such as the radionuclide-travel time and the concentration of radionuclides in water.

C.5 DISRUPTIVE PROCESSES AND EVENTS

C.5.1 IDENTIFICATION OF POTENTIALLY DISRUPTIVE PROCESSES AND EVENTS

The adverse effects of any disruptive processes or events that might occur during the next 10,000 years are considered in the comparison of sites. The identification of potentially disruptive processes or events was based on extensive review of the general literature and the reports of investigations and analyses for specific sites. The existing literature refers to a variety of phenomena that could disrupt a repository (Bingham and Barr, 1978; Burkholder, 1980; Claiborne and Gera, 1974; Cranwell et al., 1982; Davis et al., 1980; DOE, 1980, 1983; Giuffre et al., 1980; Harwell et al., 1982; Hunter, 1983; IAEA, 1983; Koplik et al., 1982; Lee et al., 1978; Arthur D. Little, Inc., 1980; Little, 1982; Long, 1980; ONWI, 1985; Pepping et al., 1983; Ross, 1986; Sandia National Laboratories, 1983; Scott et al., 1979; Stottlemyre et al., 1980; Vesely and Gallucci, 1982). The phenomena that are considered for the present analysis are listed in Table C-4. This list includes, for example, those phenomena considered by the International Atomic Energy Agency (IAEA, 1983). As indicated in Table C-4, some of these phenomena (e.g., climatic changes, glaciation, and diagenesis) were taken into account in the considerations of the nominal case. Other phenomena were considered in terms

Table C-4. Phenomena potentially relevant to release scenarios

NOMINAL CASE (EXPECTED CONDITIONS)	
Brine-inclusion migration	Geochemical changes
Buoyancy and convective cells	Geohydrology changes
Changes in rock characteristics	Localized rock fracturing
Climate changes	Sea-level changes
Corrosion	Thermal effects
Diagenesis	Thermomechanical effects
UNEXPECTED FEATURES	
Extreme changes in rock characteristics, geohydrology, or geochemistry, induced by excavation or heat generated by waste	Undetected features, such as faults, shear zones, breccia pipes, dikes, gas pockets, boreholes
DISRUPTIVE EVENTS AND PROCESSES	
Brine pockets	Human interference
Deposition	Drilling
Diapirism	Ground-water withdrawal
Dissolution	Injection
Epeirogeny	Irrigation
Erosion	Military activities
Meteorite impact	Mining
Severe-weather phenomena	Recharge
Surface-water changes	Underground storage
Tectonic activity	
Faulting	Premature failure of waste packages
Magmatic activity	Incomplete sealing of the shafts and the repository

of unexpected features (e.g., undetected faults). Those conditions not considered in these categories are evaluated under the category of disruptive processes and events.

C.5.2 PROCESSES AND EVENTS OF NEGLIGIBLE LIKELIHOOD OR IMPACT

An initial screening of these processes and events was based on impact on site performance or probability of occurrence. For this analysis, a probability of less than 1 chance in 10,000 over the first 10,000 years was considered to be negligible. The phenomena eliminated in this initial screening are discussed below.

Deposition

The deposition of material on or near a site from erosion elsewhere would increase the thickness of the overburden. Increased loading could conceivably affect the hydraulic characteristics of the site. However, analyses by Arthur D. Little, Inc. (1980) and Cranwell et al. (1982) show that there would be virtually no impact on repository performance. Therefore, this process is not considered to be potentially disruptive to a repository.

Epeirogeny

Epeirogeny involving regional uplifts or downwards may occur in stable cratonic areas. In general such processes are extremely slow and are not likely to lead to significant disruptions of a repository (Arthur D. Little, Inc., 1980; Harwell et al., 1981).

Erosion

The discussions in Section 6.3.1 of the EAs (DOE, 1986a-e) concerning the rate of erosion conclude that ongoing erosional processes do not appear to be significant at any of the nominated sites. For example, Schumm and Chorley (1983) list denudation rates in mountainous regions, such as the Himalayas, of only about 10 meters in 10,000 years. Similarly, rates for valley incision of sedimentary rock in the Colorado River region do not produce more than about 3 meters of erosion in 10,000 years. Such erosion is not expected to significantly affect a repository at least 200 meters below the surface.

Even for locations where uplift is ongoing (typically near subduction zones), erosion after 10,000 years would only amount to a few tens of meters (Schumm and Chorley, 1983). The reviews by Arthur D. Little, Inc. (1980) and Hunter et al. (1983) agree with these conclusions. Because there are no credible erosional processes that could remove sufficient overburden to affect the site conditions that are relevant to the performance measures, no scenarios were developed for repository disruption by erosion.

Formation of new brine pockets in salt

The development of a brine pocket after repository closure has also been considered. For example, brine migration induced by the heat generated by the waste may result in some leakage into the repository. Creep of the salt could then result in pressurization of this brine. However, the analyses referenced in Section 6.4.2 of the EAs for the salt sites (DOE, 1986a-c) indicate that, even for extreme assumptions, the volumes of water involved are insignificant. Larger amounts of water may be available from nearby interbeds, which could result in seepage into the repository if a connection between the interbed and the repository were to develop after closure. However, any such connection could not lead to a brine pocket within the repository because the water would be driven out by the lithostatic pressure induced by salt creep. Therefore, a scenario involving the formation of new brine pockets in salt was not developed.

Salt diapirism

Diapirism is not considered in this evaluation because there is no evidence of significant salt-dome growth at any of the sites under consideration. Furthermore, studies indicate that a salt thickness of more than 300 meters and an overburden of at least 2000 meters are needed to generate diapiric movement (Arthur D. Little, Inc., 1980). Therefore, the process is not considered to be relevant to any of the nominated salt sites.

Meteorite impacts

Meteorite impacts have been considered in many reports (Claiborne and Gera, 1974; Lee et al., 1978; Arthur D. Little, 1980; Koplik et al., 1982; Vesely and Gallucci, 1982). In all cases it was concluded that the probability of impact by a meteorite or other astrophysical body is less than 10^{-11} per square kilometer per year (i.e., approximately 10^{-7} per square kilometer over 10,000 years). This event is therefore not considered to be significant.

Severe-weather phenomena

Meteorological phenomena, such as hurricanes or tornadoes, are not expected to have a direct impact on performance. The surface flooding of the site that could be caused by such storms is not expected to be important, because the effects would be transient and of little or no long-term consequence to the repository. Tsunamis and seiches--wave phenomena associated with large bodies of water--are not of concern because such water bodies have negligible probability of occurrence at the nominated sites during the next 10,000 years.

Surface-water changes

Some reports refer to changes in surface hydrologic conditions that are possible during the next 10,000 years, including the relocation of rivers and streams, the creation of lakes, and the impoundment of waters by landslides, faulting, or engineering modifications. It is not likely that these effects would result in any direct impact on the performance of a repository because the surface-water system at any of the nominated sites does not have a significant connection with the deep geohydrologic system. Furthermore, discharge points for deep waters are not likely to be significantly affected by such changes (Cranwell et al., 1982; Vesely and Gallucci, 1982).

C.5.3 DISSOLUTION

The salt sites may be susceptible to host-rock dissolution. The existence of localized zones of dissolution and dissolution fronts at the salt sites is addressed in Chapters 3 and 6 of the EAs (DOE, 1986a-c). Any ongoing dissolution associated with these zones is not likely to have an impact on repository performance because the sites were purposely selected far enough from known dissolution fronts to avoid any intersection with the controlled area for at least 10,000 years. The existence of large undiscovered zones of dissolution that could advance to the vicinity of the repository is unlikely because dissolution features that expand at even very low rates tend to have abundant surface expression. For example, throughout the Permian Basin, features for advance rates as low as 10 centimeters per year are easily observed. In addition, data from drillhole logs and geophysical surveys in the vicinity of the sites reveal little evidence of zones of active dissolution (e.g., missing beds, major faults).

Repository performance may be adversely affected by disruptive dissolution if the repository is breached by a significant dissolution feature or if ground-water flow paths in the controlled area are affected. Breaching of the repository would greatly increase the amounts of brine available for waste-package corrosion and waste-form leaching, thereby affecting the waste-package lifetime and increasing the amount of radionuclides available for release to the surrounding ground-water system. Breaching the repository would also reduce the long travel times predicted for a salt repository under expected conditions. The interception of flow paths outside the repository could shorten travel times.

It is possible that local dissolution rates may be much higher than the regional averages, or that unexpected disruptions at the site could increase contact between ground water and the host rock. Possible disruptions of this type include climatic fluctuations, tectonic events, the fracturing of confining layers through repository-induced stresses, and human intrusion.

Climatic fluctuations could increase the rate of infiltration into the deep ground-water systems, which could in turn increase the rate of dissolution at the bedded-salt sites. However, as discussed above, such changes would not lead to a disruption of the repository in 10,000 years. Therefore, no scenario was developed for this effect.

A tectonic event like faulting could lead to a disruption of confining layers and increase the accessibility of the host salt to water. Such an event could increase the rate of advance of a dissolution front or could initiate localized dissolution, which could be significant if the fault is in the vicinity of the repository. The likelihood of faulting in the region near the salt sites is discussed later under disruptive tectonic events.

The confining units that separate the salt units from units containing relatively fresh water or unsaturated brines may be fractured. Also, existing rock fractures may open because of the excavation of the repository openings or because of the thermomechanical stresses induced by the heat generated by the waste. Fracturing induced by mining is not expected to be significant at the bedded-salt sites since the disturbance would extend less than a few room diameters into the rock and the confining sequence is hundreds of meters thick.

At the Richton Dome site, the buffer zone of salt between the repository and the flank of the dome is at least 240 meters thick, and hence mining-induced stresses are not likely to affect this zone significantly. Thermally induced stresses may be more important, however, since thermal expansion could disturb the rock at distances that extend beyond the salt. Therefore, the confining units between a host salt bed and an overlying aquifer or the caprock and the sheath that protects a salt dome from surrounding geohydrologic units could be affected. Provided the rate of dissolution is rapid enough, the disturbance could permit increased contact between the water and the host salt, thus leading to local dissolution that could adversely affect the repository. Therefore, such a disturbance was considered in developing the scenarios for disruptive events.

Human intrusion, such as exploratory drilling, could lead to pathways for water from an overlying aquifer down and through the host salt. The processes initiated by such intrusion could also involve localized dissolution and are discussed later under human interference.

Finally, the possibility of local dissolution rates higher than the average rates throughout the geologic setting could imply the possibility of an unexpected breach of the repository. Heterogeneity of the site may lead to irregularities along the leading edge of an advancing dissolution feature and variations in local dissolution rates of up to an order of magnitude. In this case, the advance of a dissolution front could be more rapid than estimates based on the regional averages would suggest. Therefore, scenarios involving an increased rate for the advance of a dissolution front were developed.

C.5.4 TECTONIC ACTIVITY

Tectonic processes include fault movement (both permanent displacement and strong ground motion), magmatic activity, folding, tilting, uplift, and subsidence. The slow, gradual processes of folding and tilting are not likely to lead to a disruption of the repository during the next 10,000 years. However, numerous studies conclude that faulting and magmatic activity are potentially significant (Arthur D. Little, 1980; Stottlemyre et al., 1980; Harwell et al., 1981; Koplik et al., 1982; Cranwell et al., 1982; Davis et al., 1983).

Faulting

The probability of faulting at given sites has been evaluated by many investigators (see, for example, Koplik et al., 1982). The available evidence strongly suggests that most fault movements in the shallow crust have followed existing zones of faulting or zones of weakness (Trask, 1982). On the basis of this evidence, the generation of new faults in unfractured material is not considered credible. Only movement along existing faults is considered.

The evaluation of faulting scenarios depends on the way the faulting affects the repository-performance factors. For example, faulting can affect the ground-water-travel time by modifying existing pathways or by creating new ones. In the extreme case of large-scale movement on a through-going major fault through the repository, the fault could create a direct pathway between the repository and the accessible environment. Strong motion from these types of events could also modify ground-water flow away from the faults, depending on the state of stress, the material properties, and the pore pressure within the affected rock. The ground-water-travel time could be affected by large movements on major faults in the controlled area; in addition, it could be indirectly affected by faulting outside the controlled area if the regional flow is affected.

Fault-induced changes in flow paths could affect the flux of water past waste packages. For example, faulting could occur through the repository and connect transmissive units that are otherwise unconnected. In these instances, an evaluation of increases in the flux through the repository involves consideration of the direction of flow, the permeability of the fault zone and aquifers, the number of waste packages affected by the faulting, and whether the changes are temporary or permanent.

If a faulting event leads to the introduction of new sources of water into the repository and along flow paths, the chemistry of the repository water could be altered. Such alteration could affect the solubility of the waste, the corrosion of the waste package, or retardation along flow paths. Retardation along flow paths could also be affected by physical changes in the fault zone. Finally, the waste-containment time may be shortened if the fault intersects the repository and disrupts any waste packages.

The five categories of faulting considered for the development of scenarios are based on three principal assumptions. First, it is assumed that large events, those capable of rupture lengths of tens of kilometers and displacements of several meters, are considered to be qualitatively different from small events that have rupture lengths of less than a few kilometers and displacements of only a few tens of centimeters or less. For this analysis, a large event is one with a Richter magnitude of more than about 6. Not only are the magnitude and rupture dimensions (length and displacement) of a large event significantly different from those of a small event, the probability of a small event may be many orders of magnitude higher than that of a large event. Second, it is assumed that an event occurring within the repository can have considerably more impact on performance than an event that occurs outside the repository. For example, in addition to impacts on the time of ground-water travel, faulting inside the repository could affect the nature of the host rock and disrupt the waste packages, thereby affecting the containment of the waste. Finally, it is assumed that the events that occur in the controlled area could have different impacts than those that occur outside the controlled area. An event inside the controlled area can have a direct impact on a performance factor (e.g., on the flow paths), while those that occur outside the controlled area would have only indirect impacts (e.g., on the hydraulic-head distributions). On this basis, the categories of faulting scenarios are (1) movement on a large fault inside the repository; (2) movement on a small fault inside the repository; (3) movement on a large fault inside the controlled area but outside the repository; (4) movement on a small fault inside the controlled area but outside the repository; and (5) movement on a large fault outside the controlled area.

For the analysis of these scenarios, the type of information described by Trask (1982) was used to aid in determining faulting probabilities. This information falls into two broad categories: (1) the neotectonic history of the region and (2) data that represent measurements of ongoing deformation.

Specific types of information include an assessment of the state of stress (stress directions and type of faulting expected), measured rates of uplift, subsidence, and tilting; patterns and levels of instrumental and historical seismicity, including published recurrence relationships (see, for example, Algermissen et al., 1982; Bernreuter et al., 1985; Electric Power Research Institute, 1985); and estimated slip rates of faults that have moved in Quaternary time. The applicability of these data is site dependent. Because of the relatively long period of interest (10,000 years), the probabilities assigned to faulting events are likely to be highly uncertain.

Magmatic activity

Magmatic activity is also considered to be a potentially significant disruption to the repository. For example, an extrusive event could exhume a fraction of the waste in the repository during the eruption and entrain the waste in the lava, ash, or gas. However, the most significant release mechanism appears to be entrainment of the waste in the lava and discharge directly to the accessible environment. A less dramatic impact is one in which local temperatures are affected by a magmatic intrusion. Local fluid conditions could be altered, and significant changes in water chemistry could result from the temperature changes. Thus, sorption factors and solubility limits could be affected. Similarly, increased temperatures could affect the rates of waste-package corrosion, decreasing the waste-package lifetime. Furthermore, the increased local temperatures could cause fracturing in the host rock because of thermomechanical or hydrothermal loadings. In this case, in addition to the above thermal effects, fluid movement in and around the repository could be affected by the creation of new ground-water pathways. Geochemical conditions could change if this fracturing allowed the intrusion of new ground water, and possibly corrosive gases, into the repository.

Magmatic activity could have a less direct impact on the repository as well. For example, extrusive activity away from the site could change the surface-water conditions by damming a nearby river. Such damming could result in large-scale flooding that could affect the site. However, the impact of surface flooding on the performance factors was judged to be insignificant for any of the sites. Therefore, the only scenarios that were developed for magmatic activity are concerned with extrusive and intrusive events that directly affect the repository.

C.5.5 HUMAN INTERFERENCE

Disruptions of the repository by human interference have been evaluated many times in the literature (IAEA, 1983; Arthur D. Little Inc., 1980; Cranwell et al., 1982; ONWI, 1985; Harwell et al., 1982; Koplik et al., 1982). Potentially significant human-interference activities that have been considered include both onsite and offsite activities.

Onsite interference

Onsite interference activities are those that would occur in close proximity to the waste-emplacement area and could result in an intrusion into the repository itself (e.g., a borehole passing through the emplacement horizon).

Most onsite activities are regarded as extremely unlikely at a repository site. The period immediately after permanent closure will be one of close technical monitoring and active institutional surveillance. This period will be one in which active institutional control by the Federal Government will provide a highly effective means of precluding potential adverse human activities at the site. For purposes of licensing and safety evaluations (40 CFR Part 191, Subpart B), such active institutional controls are relied on for a period of only 100 years after repository closure. Beyond that period, reliance is placed on passive controls, which consist of (1) a network of permanent markers in and around the site; (2) a variety of permanent records that are deployed by methods designed to perpetuate their existence and availability; and (3) the relatively low natural-resource potential of the site itself, as required by the DOE siting guidelines (10 CFR Part 960, Subpart C). These measures should provide effective protection against inadvertent human intrusions into the repository, particularly those associated with large-scale, protracted activities like solution mining.

This finding has also been made by the NRC and the EPA in their considerations of the potential significance of human interference (10 CFR Part 60 and 40 CFR Part 191, Subpart B). Consequently, the standards regarding such activities do not require the consideration of myriad scenarios for inadvertent human interference. The NRC indicates, however, that occasional penetrations of the repository (e.g., wildcat drilling at the site) over the period of interest must be evaluated. Assumptions that bound the scenarios for these activities have been specified by the EPA in 40 CFR Part 191, Subpart B.

On the basis of the NRC and the EPA regulations as well as the technical studies that form the basis for those regulations, the DOE has developed scenarios for exploratory drilling that include new pathways for radionuclide migration and the direct exhumation of radioactive materials. In the case of the salt sites, these scenarios also consider host-rock dissolution that results from drilling. In selecting the onsite scenarios for more-detailed consideration in this analysis, the DOE was guided by the conditions stipulated in the NRC and EPA regulations; by the physical characteristics of the sites under consideration, as described in the EAs; by the information available in the literature; and by the judgment of technical specialists in the relevant areas.

Offsite interference

Offsite interference includes those activities that could in some way diminish the isolation provided by the repository without physically penetrating the barriers relied on for waste containment or isolation. The offsite activities that have been considered include ground-water withdrawal, extensive irrigation, underground injection of fluids, underground storage of resources (e.g., pumped storage), military activities, and the creation of large-scale surface-water impoundments.

Offsite ground-water withdrawal could be important if the pumping results in a change in the ground-water conditions in the controlled area. However, withdrawal will generally be limited to significant sources of water that are generally capable of yielding substantial amounts of good-quality water and are sufficiently shallow to be economically exploitable. The deep units at the salt sites that might receive radionuclide releases are not likely to meet these criteria. Similarly, while some portions of the geohydrologic system important to waste isolation at the Hanford site may have the potential to be affected by ground-water withdrawal, there is no evidence that withdrawal would actually affect waste isolation either in terms of an effect on the flux through the repository horizon or a significant effect on the ground-water-travel time. With regard to the unconfined aquifer at the Yucca Mountain site, withdrawal from this body is not likely near the controlled area because of the depth to the water table in this area. Although it is possible that withdrawal could occur in the flat areas surrounding the site, such withdrawal should not adversely affect the geohydrologic conditions in the controlled area. This is because pumping from this aquifer would affect an area of only a few hundred meters around the withdrawal point.

Extensive irrigation could eventually affect the geohydrology if the recharge of the deep units is affected. However, Section 6.3.1 of the EAs (DOE, 1986a-e) indicates that, on the basis of the existing geohydrologic data, the potentiometric surfaces of the deep units relevant to repository performance at the five sites would not be adversely affected in less than 10,000 years. Thus, this activity is not likely to lead to a significant disturbance of the repository during the first 10,000 years.

Underground fluid injection could lead to a number of different kinds of disturbances. For example, fluid injection could modify the heads in the receiving unit and those connected to it. The disposal of liquid wastes could alter the geochemical regime within the controlled area. However, the sites appear to have extremely low potential for such injection. The sites were intentionally chosen because of their relative impermeability, and therefore little fluid can be taken up in the units that are important to waste isolation. Furthermore, the sites are remote and offer little incentive over injection closer to the origin of the wastes.

Fluid-injection activities also include offsite hydrofracturing, which could affect the ground-water system. Hydrofracturing has the potential to change some pathways if the fractures propagate into the controlled area. Consequently, the controlled-area boundaries will be selected so that offsite fluid-injection activities will be far enough from the repository to preclude the propagation of hydrofractures into the repository area. This will minimize the impacts of such activities on the site.

Offsite excavation for the storage of resources or pumped energy storage could have an impact if such excavations affect ground-water flow in the controlled area. However, because of the tightness of the formations (i.e., the combination of low permeability and high storativity) needed for storage, impacts on the geohydrology within the controlled area would be negligible. More important, however, is the fact that, as far as is known at present, the formations that are adjacent to each of the sites provide no unique incentives for such offsite excavation. There are vast areas in the region where such excavation could be performed as well or better, and therefore the probability of such activity in the vicinity of the repository is considered to be essentially negligible. Therefore, scenarios for these activities were not developed.

Military activities, such as large-scale weapons testing, could have an impact on site properties. This scenario is important only for the Yucca Mountain site, which is adjacent to the Nevada Test Site. The primary concern is the effects of the seismic wave induced by an underground explosion. However, at Yucca Mountain, explosion-induced disturbances would be much less significant than those from natural seismicity. Therefore, these effects would be bounded by those considered under tectonic disruptions.

The construction of major offsite surface-water impoundments (e.g., reservoirs) that could alter the hydraulic characteristics within the controlled area has also been considered. Surface-water impoundments have potential significance only if (1) the physical conditions in the vicinity of the site are such that the surface-water impoundment could be reasonably constructed (e.g., ability to dam a river), and (2) the aquifers along potential release pathways are such that the deep geohydrologic system would be changed by the construction of the impoundment. The analyses reported in Section 6.3.1 of the EAs lead to the conclusion that such impoundments would be of little consequence in the units where the transport of radionuclides could be important. Consequently, such impoundments would have a negligible impact on expected repository performance at the nominated sites.

C.5.6 PREMATURE FAILURE OF WASTE PACKAGES

Disruptions due to the premature failure of waste packages have also been considered. The performance assessments in Section 6.4.2 of the EAs (DOE, 1986a-e) considered a special "performance-limits" case in which all of the waste packages were presumed to have failed after only 300 years. The results indicate that early failure of all waste packages is not expected to have a significant impact on releases to the accessible environment. It is not difficult to understand the reason for this result. At all of the nominated sites, the expected time of ground-water-travel is on the order of tens of thousand of years. Consequently, the radionuclide-travel time must be long, and the additional residence time because of containment within the waste package of a few thousand years is only a small part of the overall delay. The effects of early waste-package failure are explicitly considered in all the disruptive scenarios in which radionuclide-travel times are significantly reduced. These include the direct-release scenarios for magmatic activity and human intrusion.

C.5.7 INCOMPLETE SEALING OF THE SHAFTS AND THE REPOSITORY

Incomplete sealing or the failure of the seals after closure could result in an increased amount of water in the repository or in a preferential pathway for radionuclide migration. Therefore, a scenario was developed to take into account the failure of seals to perform as designed.

C.6 SELECTION OF POTENTIALLY SIGNIFICANT SCENARIOS

C.6.1 INTRODUCTION

The preceding sections have discussed the conditions, events, and processes that are judged to have a significant probability of affecting the performance of the repository at the nominated sites. In this section, scenarios judged to be applicable to these conditions are defined in terms of the sequences of processes and events that may have potential impacts on performance. In Appendix D, these potentially significant scenarios will be expressed in terms of site-specific characteristics. Values for the performance factors and for the probabilities of the scenarios at each site will be estimated. The estimates may indicate that a scenario need not be considered at a particular site, because of negligible likelihood of occurrence or negligible consequence.

Scenarios were developed in terms of potential impacts on the performance of the repository (i.e., waste containment and isolation). Therefore, the processes and events of concern are those that can reasonably lead to the following types of disruption:

- The release of radionuclides directly into the accessible environment.

- A modification of site conditions such that the expected repository performance is significantly affected.

Scenarios for direct releases of radionuclides into the accessible environment are important because the primary barriers relied on for containment and isolation may be bypassed. The consequences then depend on the fraction of the waste in the repository that is affected by the disruption and the time when the disruption occurs. An event that occurs early (e.g., before 500 years) may be qualitatively different than one that occurs later because the inventory of radionuclides in the waste packages is very high in the early years. The approach taken here is to estimate direct releases for an "early" disruption (i.e., within the near-term thermal period of about 500 years) and for a "late" disruption (i.e., between 500 and 10,000 years). The evaluations of the scenarios in terms of estimated direct releases are likely to be dominated by the assumptions in the scenarios (e.g., the number of packages affected), rather than site characteristics; therefore, the relative merits of sites may be masked. For this reason, a comparison of sites on the basis of direct-release scenarios must be judicious, with due regard for the assumptions in the model.

The second category of disruptive scenarios covers indirect releases to the accessible environment because of disruptions of the engineered barriers and transport through the natural barriers. In this case, the significance of the impacts depends on the site characteristics that influence these barriers. Thus, the factors considered in the evaluation of expected conditions (e.g., waste-package lifetime, rate of waste dissolution, and radionuclide-travel time) are relevant in the evaluation of these indirect-release scenarios. The impacts of the disruptive processes and events on the site characteristics and conditions affecting the repository-performance factors (Table C-1) are then taken into account. For example, a disturbance that changes the expected chemical conditions at the site could lead to increased waste-package corrosion rates and early loss of containment. Likewise, an event that increases the rate of ground-water flow past the waste, such as a disruption that creates a local flow path through the repository, may lead to an increased rate of release from the engineered-barrier system. Changes in regional ground-water-flow conditions, such as fluctuations in climate and recharge, may result in modifications to the hydraulic gradients that control local flow conditions.

In summary, the direct-release scenarios are evaluated in terms of release estimates, and the indirect-release scenarios are evaluated in terms of impacts on repository-performance factors. The scenarios that are evaluated are those that have at least 1 chance in 10,000 of occurring in 10,000 years. Scenarios that are judged to have a lower probability of affecting performance are not considered in this evaluation, unless the impact on expected repository performance is extremely significant.

It is conceivable that scenarios involving combinations of disruptive events may need to be developed. For example, a combination of movement on a large fault and human intrusion at a site could lead to large impacts on site performance. However, if these phenomena are independent of each other, the probability that both occur within the first 10,000 years and lead to impacts on performance will generally be much lower than that for the individual events. Thus, for the disruptive events in which each event has low probabilities, the scenario for multiple independent events will have negligible probability.

There are several ways in which scenarios for multiple events could be significant, however. First, a combination of a disruptive event and expected conditions, such as a fault movement coupled with expected climatic changes, may have a probability that is not negligible. In this case, it is not necessary to develop a new scenario for the combination of events; it is only necessary to consider the full range of expected conditions when evaluating any of the disruptive processes or events.

A second way in which combinations of disruptive processes and events may be significant occurs when the phenomena are not independent; for example, a scenario for causally related phenomena may have a probability not significantly lower than that for the initiating event. A specific example might be a scenario in which human intrusion leads to enhanced dissolution at a salt site. Such common-cause events and processes are taken into account in the specific development of the scenarios.

C.6.2 SCENARIO 1: NOMINAL CASE (EXPECTED CONDITIONS)

It is assumed that the processes operating in the geologic setting during the Quaternary Period continue to operate over the next 100,000 years. The nominal case scenario is based on the existing geohydrology, geochemistry, and rock characteristics and on the changes expected in these conditions because of natural processes, the effects of repository excavation, and the emplacement of heat-generating waste.

The conditions are modified with time because of expected worldwide climatic changes. In particular, it is assumed that precipitation increases over the next 15,000 years. Ongoing erosion and dissolution rates do not have significant effects on performance, and there are no human activities (beyond repository construction and waste emplacement) that interfere with repository performance. For a period of several thousand years after emplacement, the waste packages provide substantially complete containment of the waste. There is no significant leakage through shaft, borehole, and repository seals, and these seals do not provide preferential pathways for radionuclide transport.

The nominal case for the salt sites is slightly different than that for the Hanford and the Yucca Mountain sites. For the salt sites there is no measurable ground-water flux through the host rock. After the emplacement of the waste packages, brine inclusions in the salt migrate toward the packages because of temperature gradients resulting from the heat generated by the waste. This process provides a potential source of water in the neighborhood of the waste package and continues until the gradient diminishes to a low level. Brine may also seep into the repository openings through any interbeds in the vicinity of the repository horizon. The presence of brine in the vicinity of the package leads to the corrosion of package components and loss of containment at some point. After the waste package fails, brine not consumed by corrosion is available to dissolve the waste. The amount of dissolution is determined by the solubility of the waste-form constituents and the radionuclides. Radionuclides dissolved into the brine are considered to be released from the engineered-barrier system. Radionuclides dissolved from the waste are free to be transported into the accessible environment. Since the movement of water through the host rock is negligible, it is assumed that the mechanism for the transport of radionuclides through the salt is diffusion induced by the radionuclide-concentration gradient. This process continues until concentration gradients are negligible or until the radionuclides reach a relatively transmissive unit. In the latter case, the waste is transported by moving ground water to the accessible environment. Heterogeneity may affect the travel time. The retardation of radionuclides relative to the water movement is assumed to be insignificant for the salt sites.

The nominal case for the Hanford and Yucca Mountain sites assumes that there is a measurable ground-water flux through the host rock. The waste packages fail at some point because of corrosion under the thermal, fluid, and chemical conditions expected in the repository. Flow through the repository leaches radionuclides from the waste at a rate determined by the waste form and radionuclide solubility and the flow rate of water in contact with the waste. The radionuclides dissolved into the ground water are then transported advectively by the ground-water through the host rock to relatively transmissive units that transport the radionuclides to the accessible environment. The radionuclide transport depends on the hydraulic properties of the units and the physical and chemical retardation of radionuclide movement relative to the ground-water movement. Again, geohydrologic and geochemical heterogeneities may affect the radionuclide-travel time.

C.6.3 SCENARIO 2: UNEXPECTED FEATURES

The scenario for release because of unexpected features is the same as for the nominal case, except that the conditions that affect release from the engineered-barrier system or transport through the natural barriers are much more extreme than those considered for the nominal case. Unexpected features include those due to excavation and heat-induced subsidence and uplift, undetected geologic features, or other unknown features. These unexpected features introduce extreme conditions with respect to rock characteristics, geohydrology, or geochemistry.

C.6.4 SCENARIO 3: REPOSITORY-INDUCED DISSOLUTION OF THE HOST ROCK

Expected conditions prevail, except that the thermally induced expansion of the overburden results in fracturing and the opening of existing fractures that allow access to the soluble host rock by relatively fresh water from an overlying aquifer. Localized dissolution proceeds, driven by existing hydraulic gradients and flow paths and accelerated by temperature increases due to the waste. The dissolution zone penetrates the host rock and intersects the repository in less than 10,000 years, thereby introducing water into the repository and providing a hydrologic connection between the repository and the accessible environment. Waste-package corrosion, as well as the amount of water available for the dissolution of radionuclides, is increased. Chemical conditions correspond to those associated with brine saturated with dissolved salt rather than to those of the in-situ brine inclusions. The radionuclides can now migrate through the dissolution zone to the overlying aquifer.

C.6.5 SCENARIO 4: ADVANCE OF A DISSOLUTION FRONT

Expected conditions prevail, except that variability in site characteristics results in local dissolution of the salt units at a rate that is accelerated relative to those estimated from regional average dissolution rates. The dissolution front advances and breaches the repository in less than 10,000 years, permitting significant amounts of water to enter the repository and providing a hydrologic connection between the repository and the accessible environment. Waste-package corrosion, as well as the amount of water available for the dissolution of radionuclides, is increased. Chemical conditions correspond to those of brine saturated with dissolved host salt rather than to those of the in-situ brine inclusions. The radionuclides can now migrate through the dissolution zone to the overlying aquifer.

C.6.6 SCENARIO 5: MOVEMENT ON A LARGE FAULT INSIDE THE CONTROLLED AREA BUT OUTSIDE THE REPOSITORY

Expected conditions prevail, except that movement occurs on an existing, large through-going fault that is located in the controlled area but does not intersect the repository. The fault connects transmissive units above and below the repository or may extend to the surface. The rupture length is many kilometers, while displacement is on the order of 0.50 to 2.0 meters. The ground-water-travel time may be decreased. Although geochemical conditions may be temporarily affected if flow is directed across fresh mineral surfaces, any such effect is transitory, and it is assumed that prefaulting conditions are not substantially changed.

C.6.7 SCENARIO 6: MOVEMENT ON A LARGE FAULT WITHIN THE REPOSITORY

Expected conditions prevail, except that movement occurs on an existing large through-going fault that intersects the repository. Waste packages may be sheared. The fault connects transmissive units above and below the repository or may extend to the surface. The rupture length is many kilometers, while displacement is on the order of 0.50 to 2.0 meters. In addition to impacts on the ground-water-travel time, the flux through the repository may be increased, permitting increased dissolution of waste.

C.6.8 SCENARIO 7: MOVEMENT ON A SMALL FAULT INSIDE THE CONTROLLED AREA BUT OUTSIDE THE REPOSITORY

Expected conditions prevail, except that movement occurs on existing small faults that are within the controlled area but do not intersect the repository. The faults are not large in vertical extent and are likely to rupture over only a few formations. The movement connects transmissive units above or below the host rock. There is no connection with the land surface. The rupture length is a few kilometers, while the net displacement is less than about 50 centimeters. The ground-water-travel time may be reduced if the faulting connects the normal receiving units with more transmissive units.

C.6.9 SCENARIO 8: MOVEMENT ON A SMALL FAULT WITHIN THE REPOSITORY

Expected conditions prevail, except that movement occurs on existing small faults that intersect the repository. Waste packages may be disturbed or sheared. The faults are not large in vertical extent and are likely to rupture over only a few formations. The fault movement connects the repository with transmissive units immediately above or below the repository. There is no connection to the land surface. The rupture length is a few kilometers, while displacement is less than 50 centimeters. Flux through the repository may be increased if the faults were previously filled with secondary minerals. The containment of some waste packages may be lost because of damage caused by the faulting.

C.6.10 SCENARIO 9: MOVEMENT ON A LARGE FAULT OUTSIDE THE CONTROLLED AREA

Expected conditions prevail, except that movement occurs on existing large faults outside the controlled area. The length of rupture is tens of kilometers, and displacement is on the order of several meters. The event is large enough to be capable of altering the hydrologic system in the controlled area. In this case, both ground-water travel time and flux may be affected.

C.6.11 SCENARIO 10: EXTRUSIVE MAGMATIC EVENT

Expected conditions prevail, except that magma rises from an underlying source through the earth's crust as a thin, elongated dike. The dike intercepts a fraction of the waste packages, which fail immediately. Waste from these packages is incorporated into the magma. Two time periods are considered for this event: (1) early, within 100 to 500 years after closure, and (2) late, between 500 and 10,000 years after closure. Waste is carried to the surface, where it can be released into the accessible environment by the weathering and erosion of the cooled lava.

C.6.12 SCENARIO 11: INTRUSIVE MAGMATIC EVENT

Expected conditions prevail, except that magma rises as a thin elongated dike from an underlying source through the earth's crust. The dike intercepts the repository and causes sharp temperature increases out to a distance of about 10 meters from the dike, with temperatures in the surrounding rock exceeding 1000°C. Because of the temperature increases, waste packages in the vicinity of the dike can fail early. Dissolution rates for the waste may be increased because of the impacts of these thermal conditions on solubility. The host rock may be fractured thermomechanically or hydrothermally, and the rates of ground-water flow through the repository may be increased in the vicinity of the dike after cooling.

C.6.13 SCENARIO 12: LARGE-SCALE EXPLORATORY DRILLING

Expected conditions prevail, except that large-scale drilling occurs within the controlled area. On the basis of specifications in 40 CFR Part 191, Appendix B, it is assumed that 30 boreholes per square kilometer are drilled through the repository in 10,000 years. For release of radionuclides directly to the land surface, it is assumed that a nearly direct interception of a waste package by an exploratory borehole would be required. The fraction of the boreholes that could contribute to direct release is estimated from area considerations. For example, for vertical emplacement of waste packages, the effective cross-sectional area for the interception is estimated to be about 4 square meters, assuming that the diameters of the waste-emplacement borehole and the exploratory borehole are 2 and 0.25 meters, respectively, and that the effective target area has a diameter that is the sum of these two. For a repository with an area of 8 square kilometers and containing 16,000 packages, the average area per package is 500 square meters. Therefore, roughly 1 percent of the boreholes are close enough to waste packages to allow for direct release to the land surface in this example.

The boreholes may also contribute to release by providing preferential pathways for radionuclides to migrate to aquifers in which radionuclides may be transported to the accessible environment. The fraction of boreholes that could contribute to these indirect-release pathways is also estimated on the basis of area considerations. It is assumed that the radionuclides that would be available for these indirect releases are those found within the waste package or within the disturbed zone around the waste package. The diameter of this disturbed zone is taken to be about three times the diameter of the borehole. Thus, the composite effective diameter of the target zone for the example considered above would be about 7.5 meters, which implies an effective cross-sectional area of about 45 square meters. Therefore, for this example about 10 percent of the boreholes would be close enough to waste packages to intersect released radionuclides. However, not all of these boreholes may provide pathways leading to indirect release to the accessible environment. It is assumed that, for a borehole to provide such a pathway, it must connect transmissive units above and below the repository. About 80 percent of the boreholes are assumed to be deep enough to reach transmissive units 1000 meters or more below the repository horizon. Thus, on the order of 8 percent of the boreholes would provide preferential pathways for indirect releases of radionuclides to the accessible environment in this example. The estimates of actual fractions of boreholes contributing to direct or indirect releases will depend on the site-specific area per waste package.

If pumping is required for a direct release, it is assumed that 200 cubic meters of water is released to the surface per borehole (40 CFR Part 191, Appendix A). The borehole permits water from overlying units to flow through or into the repository, and the waste packages in proximity to the boreholes are assumed to fail immediately. The flow through the borehole provides a source of water for the dissolution of the waste. The water flowing into the repository may have a different composition than water in the host rock under expected conditions; therefore, the change in geochemistry may further affect dissolution rates. The borehole can provide a pathway with a ground-water-travel time different from that under expected conditions.

C.6.14 SCENARIO 13: SMALL-SCALE EXPLORATORY DRILLING

The scenario is similar to that for the scenario 12 except that less drilling is considered. In this case, it is assumed that three boreholes per square kilometer intersect the repository in 10,000 years. All other effects and percentages are assumed to be the same as specified in scenario 12.

C.6.15 SCENARIO 14: INCOMPLETE SEALING OF THE SHAFTS AND THE REPOSITORY

Expected conditions prevail, except that some shafts and tunnels are incompletely sealed. It is assumed that the seals may have an effective conductivity as high as 10 meters per year. This conductivity may permit flooding of the repository and provide a preferential pathway for radionuclide migration to the accessible environment. Because increased amounts of water may be available, waste packages may fail early, and the dissolution of waste may be increased. The time of ground-water travel to the accessible environment may be decreased.

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Appendix D

SITE RATINGS ON POSTCLOSURE REPOSITORY PERFORMANCE

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Appendix D

SITE RATINGS ON POSTCLOSURE REPOSITORY PERFORMANCE

D.1 INTRODUCTION

For each of the nominated sites, the conditions, processes, and events that could affect the performance of a repository were examined (see Sections C.1 through C.5 of Appendix C), and 14 scenarios were identified as having the potential in terms probability and consequences for significantly affecting repository performance. These scenarios are described in generic terms in Section C.6. In this appendix, detailed descriptions of the 14 scenarios are provided for each of the five nominated sites along with estimates of probabilities and scores against the performance measures. The site-specific details for each scenario are based on information given in Sections 6.3.1 and 6.4.2 of the environmental assessments for the nominated sites (DOE, 1986a-e).

The probabilities and scores were assessed by a panel of postclosure technical specialists (see Table A-2), with procedural guidance from members of the methodology lead group (see Table A-1). The process can be summarized as follows. For each scenario at a particular site, one member of the panel presented the site-specific details of that scenario, including any probability estimates from the literature, to the other members. After discussion, each panel member provided best-judgment, high-probability, and low-probability estimates for the occurrence of the scenario during the first 10,000 years after repository closure. The probability estimates were collected, tabulated, statistically summarized, and presented to the panel for discussion. After discussion, the panel arrived at a set of high-probability, base-case, and low-probability estimates for the scenario at a given nominated site. If the high probability was judged to be less than 1 chance in 10,000 over the first 10,000 years, the scenario was dismissed from further consideration unless the potential consequences in terms of releases were estimated to be extraordinarily great. By this process, probabilities were assessed for 13 of the 14 scenarios examined for each site. The probability of scenario 1--the nominal case--was obtained by summing the probabilities of the 13 other scenarios and subtracting the result from unity.

To score a scenario for a given site against the performance measures, one member of the panel presented the site-specific details of that scenario to the other members. After discussion, the performance factors F and T_1 were calculated on the basis of agreed-on estimates of the various site characteristics. These characteristics included the median time of ground-water travel, radionuclide-retardation factors, etc., as described in Section B.3.2. After any further discussion was concluded, each panel member provided best-judgment, high, and low scores for the scenario against the performance measures for the first 10,000 years and for the period 10,000 to 100,000 years after closure (Figures B-3 and B-4 and Tables B-1 and B-2). The high score was based on the judgment that the site characteristics and the corresponding release estimates were such that there was only 1 chance in 20 that the actual characteristics and releases would be even more favorable. Conversely, the low score was based on the judgment that the expected site characteristics and corresponding release estimates were such that there was only 1 chance in 20 that the actual characteristics and releases would be even less favorable. The scores were collected, tabulated, statistically summarized, and presented to the panel for discussion. After a period of discussion, the panel recommended a set of high, base-case, and low scores for the site-specific scenario for each performance measure.

Some of the information used to make these judgments is summarized in Tables D-1, D-2, and D-3. Table D-1 lists the information needed to estimate the performance factors for the potential dissolution of radionuclides under expected conditions. This table lists the solubility limits for various radionuclides and the uranium dioxide ceramic waste form. These solubility limits, along with the time-dependent mass fractions given in the environmental assessments and the supporting references, are used to estimate isotope-concentration limits, C_i. The resulting sum of the ratios of C_i to the release limits, RL_i, specified by the U.S. Environmental Protection Agency in 40 CFR Part 191 (EPA, 1985) are also given in Table D-1 as a function of time. These sums, multiplied by the appropriate volumes of water, provide the F factors for use in the evaluation of the sites.

Table D-1. Solubility factors for evaluating potential waste concentration limits at the nominated sites

Element	Solubility limit (ppm)		
	All salt sites[a]	Hanford	Yucca Mountain
C	0.06	0.056	Large[b]
Se	0.001	7.9	--
Sr	0.8	9×10^2	85
Tc	0.001	0.99	Large[b]
Sn	0.0001	1.3	0.00013
I	6×10^5	1.29×10^5	Large[b]
Cs	6×10^5	1.4×10^3	Large[b]
Ra	0.00042	0.24	1.9
Th	0.001	0.23	--
Np	0.001	2.4	720
Pu	0.001	2.4	0.43
Am	0.0001	0.00024	0.0024
Cm	0.001	--	--
Waste form (UO_2)	0.001	0.24	50

Time (years)	$\sum C_i/RL_i$ (per 1000 MTHM/m^3)		
	All salt sites	Hanford	Yucca Mountain
1,000	1.5×10^{-8}	4.2×10^{-6}	5.3×10^{-4}
10,000	3.8×10^{-9}	1.1×10^{-6}	2.2×10^{-4}
100,000	1.6×10^{-10}	4.5×10^{-8}	9.4×10^{-6}

[a]Solubility in water. Values may be smaller in saturated brine.
[b]Solubility controlled by the dissolution of the waste form.

Tables D-2 and D-3 present estimates of the performance factors F and T_1 and pertinent characteristics for each site under expected conditions. Table D-2 gives the estimates for the first 10,000 years, and Table D-3 gives the same information for the period 10,000 to 100,000 years after closure. The values of F are derived from the sums in Table D-1 and the estimated volumes of water available for dissolution. These estimates are explained in the evaluation of the various scenarios described below.

D.2 DAVIS CANYON SITE

Scenario 1: Nominal case (expected conditions)

For the purposes of this analysis, it was assumed that a repository at the Davis Canyon site would be constructed in the Paradox Formation, a thick (about 800 m) sequence of interbedded salt, anhydrite, shale, dolomite, and limestone. The repository would be located entirely within Cycle 6, a salt bed approximately 60 m thick at a depth of about 900 m from the surface. It was assumed that the mined area occupies less than 30 percent of the underground repository area and that spent fuel equivalent to 70,000 metric tons of heavy metal (MTHM) would be distributed in about 16,000 waste packages (4.6 MTHM per package) over a total area of about 8 km^2.

To estimate the volume of water available for waste dissolution in the first 10,000 years after closure, both brine migration and leakage from interbeds or through the shaft and repository seals must be considered. Estimates of brine migration in the salt range between 0.04 to 0.8 m^3 of high-magnesium brine per waste package, which was assumed to be available for waste-package corrosion and waste dissolution. The amount of leakage from interbeds or through the shaft and repository seals is difficult to estimate, but an upper bound can be calculated by considering the available void volume in the repository. This volume is expected to change with time because of salt creep. If the openings are assumed to close to about 1 percent of the excavated void space, the void volume would be 3300 m^3 per 1000 MTHM. This volume therefore represents an upper bound for the amount of brine that could be available for waste dissolution. Estimates of waste-package lifetime range from more than 2700 years for unlimited brine to much longer times for a limited volume of water. The brine available for the dissolution of the waste is estimated to range between less than 170 m^3 per 1000 MTHM to 3300 m^3 per 1000 MTHM. No other significant source of water is expected at the site for the first 10,000 years. As explained in the EA (DOE, 1986a), brine migration is not expected after the first 10,000 years because the thermal gradients that induce this migration will have decreased to negligible levels by this time. Likewise, no additional leakage into the repository from other sources is expected after the first 10,000 years because salt creep will reduce the void space and limit further inflow. Therefore, no additional volume of water is considered for the period 10,000 to 100,000 years after closure.

The concentration limits used in the EA analyses are based on solubility data in the literature and are given in Table D-1. The panel considered the possibility that the values at the site could be as much as 10 times higher

Table D-2. Site characteristics and performance factors for the nominal case for the time period 10,000 to 100,000 years after closure

Parameter	Davis Canyon	Deaf Smith	Richton Dome	Hanford	Yucca Mountain
	Site				
Volume of water available for dissolution of waste, Q (m^3/1000 MTHM)	0 to 3300	0 to 4000	0 to 3300	100,000 to 120,000	0 to 18,000
$\sum_i$ C/RL (1000 MTHM/m^3)	3.8×10^{-12} to 3.8×10^{-8}	3.8×10^{-12} to 3.8×10^{-8}	3.8×10^{-12} to 3.8×10^{-8}	4.1×10^{-10} to 4.1×10^{-6}	2.2×10^{-8} to 2.2×10^{-4}
F	0 to 1.3×10^{-4}	0 to 1.5×10^{-4}	0 to 1.3×10^{-4}	4.1×10^{-5} to 4.3×10^{-1}	0-4
Median ground-water-travel time, T (years)	230,000 to 400,000[A]	45,000 to 170,000[A]	10,000,000 to 35,000,000[B]	22,000 to 83,000	42,000 to 200,000
Retardation, R	1	1	1	1 to 200,000	100 to 1,000
Other travel time (years)	$>10^6$	$>10^6$	--	--	--
Total radionuclide-travel time, T (years)	Very long ($>1.2 \times 10^6$)	Very long ($>10^6$)	Very long ($>10^7$)	22,000 to 1.6×10^{10}	4.3×10^6 to 2×10^8
Waste-package lifetime (years)	2700 to very long	2700 to very long	4800 to very long	4,500 to 8,500	3,000 to 30,000

[A]Travel time in nonsalt transmissive units.
[B]Based on Darcy flow through salt.

Table D-3. Site characteristics and performance factors for the nominal case for the time period 10,000 to 100,000 years after closure

Parameter	Site				
	Davis Canyon	Deaf Smith	Richton Dome	Hanford	Yucca Mountain
Volume of water available for dissolution of waste, Q (m^3/1000 MTHM)	0	0	0	18 to 180,000	0 to 100,000
$\sum_i$ C/RL (1000 MTHM/m^3)	1.6×10^{-13} to 1.6×10^{-9}	1.6×10^{-13} to 1.6×10^{-9}	1.6×10^{-13} to 1.6×10^{-9}	4.5×10^{-12} to 4.5×10^{-8}	9.4×10^{-10} to 9.4×10^{-6}
F	0	0	0	8.1×10^{-11} to 8.1×10^{-3}	0-0.94
Median ground-water-travel time, T (years)	230,000 to 400,000[A]	45,000 to 170,000[A]	10,000,000 to 35,000,000[B]	22,000 to 83,000	42,000 to 200,000
Retardation, R	1	1	1	31 to 200,000	100 to 1,000
Other travel time (years)	$>10^6$	$>10^6$	--	--	--
Total radionuclide-travel time, T (years)	Very long ($>1.2 \times 10^6$)	Very long ($>10^6$)	Very long ($>10^7$)	22,000 to 1.6×10^{10}	Very long ($>4.3 \times 10^6$)

[A]Travel time in nonsalt transmissive units.
[B]Based on Darcy flow through salt.

and 1000 times smaller than those in the table. The F-factor estimates based on these concentration limits and on the volume of brine that might be available for dissolution are given in Tables D-2 and D-3.

The Paradox Formation is relatively impermeable, with a representative hydraulic conductivity of less than 10^{-6} m/yr. Overlying the Paradox Formation, and more than 400 m from the repository horizon, there are units that are more transmissive (conductivity about 1 m/yr) and could yield some water. Well below the repository horizon (900 m) and separated from it by impermeable units are more-transmissive units (conductivity about 10 m/yr). The gradient between the overlying unit and the underlying unit is downward. Gradients within subunits in the Paradox Formation are not well known and could be up or down. It is difficult to model the geohydrology of these relatively transmissive units, and estimates of the median time of ground-water travel to the accessible environment range between 100,000 and 900,000 years in the underlying units, depending on the distance to the accessible environment. If the distance to the accessible environment is 1 km, the median time of ground-water travel is estimated to lie between 120,000 and 240,000 years. For a distance of 2 km, the median time of ground-water travel is estimated to range between 230,000 and 430,000 years.

The radionuclide-travel time depends on the time of ground-water travel in these relatively transmissive underlying units. The retardation of radionuclide movement relative to ground-water movement is not high for brines, and retardation was neglected altogether in the EA evaluations. In addition to the travel through the transmissive units, the radionuclides must travel through the host salt and the confining layers between the host rock and the transmissive units. The EA for Davis Canyon (DOE, 1986a) estimates that more than 1 million years would be needed for the diffusive transport of radionuclides through 20 m of salt. The travel time through the host salt and other confining layers is therefore estimated to be much longer than 1 million years.

The site characteristics and the resulting performance factors for this scenario are summarized in Tables D-2 and D-3 for performance during the first 10,000 years and during the period 10,000 to 100,000 years after closure. These performance factors indicate that there is a high degree of confidence in the performance of the site. For example, independent of the waste-package lifetime or any other consideration, release to the accessible environment is judged to be insignificant because the median time of radionuclide travel to the accessible environment is estimated to exceed 1 million years because of the containment expected from the salt. On the other hand, even if the concentration limit alone were considered, neglecting any other isolation or containment factors, the total release to the accessible environment is estimated to be less than 1.3×10^{-5} of the EPA release limits. Therefore, even if the radionuclide-travel time is neglected, it is likely that the EPA limits would be easily met. Therefore, it is the judgment that the estimated releases would be insignificant. However, uncertainties in the expected conditions could lead to ranges in the performance factors. Thus, the base-case score is judged to be 10, with a low score of 8, for both the first and the second performance measures.

Scenario 2: Unexpected features

Figure D-1 lists the unexpected features that are considered possible at the Davis Canyon site and the various effects they could exert. The first is repository-induced subsidence and uplift, which could result from the effects exerted on the rock mass above the underground facility by the excavation of the repository and the emplacement of waste. These effects could be so severe, for example, that a pathway extending from the repository facility all the way to the overlying aquifer could be developed. Also, at the margin of the zone of subsidence, offsets could occur, and these offsets could lead to a high-permeability, high-porosity zone extending through all of the overlying sediments. Such a disturbance, if it occurred, would clearly affect the local geohydrologic conditions and the performance of the repository.

Small-scale folding of the type that has been observed for some bedded salts was also considered. However, the panel considered that any effects beyond those considered for the nominal case would be either insignificant or unlikely.

Variations in the sedimentary facies at the site, particularly near the repository horizon, could affect conditions at the site. For example, an overlying interbed may be undetected at a site because of variation between the exploratory boreholes. Such an interbed in the extreme case could provide an insulating layer that affects temperatures near the repository or the strength properties of the rock. These differences, if large, could affect other aspects of the system, such as aspects of the geohydrology or the degree of heat-induced diagenetic effects. If some of the strata pinch out away from the site, estimates based on continuous units may misrepresent the ground-water behavior.

Zones of brecciation due to local dissolution could lead to some effects—for example, on the geohydrologic conditions—beyond those expected at the site. If the zone permits rapid flow of water and if the kinetic effects of the geochemistry are important, the geochemical conditions could be different from the expected range.

If zones of increased porosity are present in the host salt, the rock characteristics and hydrologic properties would be much different from those expected. Brine pockets, either isolated inclusionary pockets or large zones of increased porosity saturated with brine, have not been detected at the site, but, if present, could have important effects because they would provide a source of water not considered before. These pressurized pockets could affect rock characteristics, hydraulic properties and flux, and geochemical conditions. Similarly, pressurized gas pockets could affect the strength properties of the rock.

Undetected fractured brittle beds in the vicinity of the repository could affect the strength of the rock and the hydrologic conditions. Such beds were considered in evaluating the range of expected conditions, but here the concern is for extreme conditions (e.g., a transmissivity or flux that are significantly outside the range considered in the nominal case).

UNEXPECTED FEATURES ↓	ROCK CHARACTERISTICS		GEOHYDROLOGY				GEOCHEMISTRY			
	DRAMATIC DIFFERENCE IN HEAT CONDUCTION	DRAMATIC DIFFERENCE IN MECHANICAL STRENGTH & DEFORMATION	DRAMATIC DIFFERENCE IN GROUND-WATER FLOW MECHANISM	DRAMATICALLY DIFFERENT GROUND-WATER FLOW PATHS	DRAMATIC DIFFERENCE IN HYDROLOGIC PROPERTIES	DRAMATIC DIFFERENCE IN HYDRAULIC GRADIENT	DRAMATIC DIFFERENCE IN SOLUBILITY, LEACH RATE, CORROSION, ETC., DUE TO TEMPERATURE INCREASE	DRAMATIC DIFFERENCE IN GROUND-WATER CHEMISTRY FROM NEW WATER SOURCE	DRAMATIC DIFFERENCE IN LOW-GRADE METAMORPHISM OF ROCK, BACKFILL	DRAMATIC DIFFERENCE IN STATE FROM EQUILIBRIUM TO KINETIC
REPOSITORY - INDUCED SUBSIDENCE/UPLIFT		●	●	●	●	●				
UNDETECTED SMALL-SCALE FOLDING										
UNDETECTED LATERAL FACIES CHANGE	●	●	●	●	●				●	
UNDETECTED BRECCIA PIPES			●	●	●	●				●
UNDETECTED ZONES OF INCREASED POROSITY	●	●			●					
UNDETECTED BRINE POCKETS	●	●			●		●		●	
UNDETECTED PRESSURIZED GAS POCKETS		●								
UNDETECTED FRACTURED NON-SALT BEDS		●	●	●	●					
UNDETECTED SMALL-SCALE FAULTING			●		●					
OTHER	●	●	●	●	●	●	●		●	

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Figure D-1. Unexpected features at the Davis Canyon site.

Although there is no evidence of faulting in the Paradox Formation at the site, particularly in the ductile salt units, the existence of small-scale faults could lead to a different conceptual model of the hydrologic conditions at the site.

Small-scale folding, of the type that has been observed for some bedded salts, we also considered. However, the panel concluded that any effects beyond those considered for the nominal case would be either insignificant or unlikely.

The "other" category includes all other unexpected features that could lead to extreme conditions at the site. This category could include renewed folding or diapirism of the Gibson Dome, for example, or the possibility that there may be some Darcy flow through the salt that is not considered to be credible at present.

Even under these extreme conditions, the releases to the accessible environment were judged to be extremely small. The base-case score assigned to the site is 9. It is based on the prediction that the site would have an extremely small release from the engineered-barrier system and an extremely long ground-water travel time even under these extreme conditions; for example, the presence of undetected dissolution features in proximity to the repository is not likely to simultaneously change these factors significantly. However, the panel could not exclude the possibility of some very small releases under the extreme range of conditions. Therefore, because of the high degree of uncertainty and the difficulty in evaluating the effects of such uncertainties under these extreme conditions, the low-estimate score is judged to be 5. The high score is judged to be 10.

The possibility that the undetected features listed in Figure D-1 exist at the Davis Canyon site is very low, but it cannot be entirely ruled out at present. The base-case probability that these features may exist and that they could lead to the extreme conditions is judged to be about 0.014, with a range from zero to 0.1.

<u>Scenario 3: Repository-induced dissolution of the host rock</u>

The heat generated by the emplaced waste could cause an expansion of the host rock that would extend to adjacent, and more brittle, interbeds. However, at the Davis Canyon site the interbeds that are close enough to the host salt cycle to be affected by thermal expansion are relatively impermeable and are expected to contain little or no water. Thus, the transmission of water from these units is extremely unlikely even if such fracturing of the rock between the repository and the interbeds were to occur. Therefore, this scenario was eliminated from consideration for the Davis Canyon site.

<u>Scenario 4: Advance of a dissolution front</u>

There are two known and two suspected dissolution features in the vicinity of Davis Canyon: the Lockhart Basin, the Beef Basin, the Needles Fault Zone, and Shay Graben. The closest of these features (the graben system) is 16 km from the site. Available data indicate that there are no dissolution features closer to the site. The rate of dissolution associated with these features is unknown at present; however, for the purposes of this evaluation, data for dissolution fronts in other basins can be used. Sixteen investigations conducted at the site of the Waste Isolation Pilot Plant in New Mexico and in the Texas Panhandle have found horizontal dissolution rates ranging between 0.07 and 98 cm/yr. In most of these cases (15 out of the 16), the rate of advance is less than 15 cm/yr. Abundant surface indicators of the dissolution exist even for features with these low rates of advance. In view of the slow rate of advance for these cases and because no surface expression of dissolution is present in the area of the Davis Canyon site, it does not seem likely that any of the dissolution features in the area are migrating laterally at a rate higher than 15 cm/yr. In order for a dissolution front advancing from the nearest dissolution feature to breach the repository in 10,000 years, a dissolution rate more than 10 times would have to be sustained. Thus, this scenario was judged to have a negligible probability of occurrence at the Davis Canyon site.

Scenario 5: Movement on a large-scale fault inside the controlled area but not through the repository

There are no known faults that intersect the repository horizon in the proposed controlled area. Whereas the existence of minor faults that may offset the basement strata cannot be ruled out, no faults that show indications of having the potential for generating a large earthquake (magnitude greater than about 6) appear to be present. The Quaternary fault nearest to the site is associated with Shay Graben, at a distance of about 16 kilometers. Recurrence statistics from Algermissen et al. (1982), adjusted to the size of the controlled area, suggest that the probability of an earthquake with a magnitude greater than about 6 is on the order of 10^{-7} per year. The faulting at Shay Graben may be related to salt dissolution and thus may not be seismogenic. Given the absence of known seismogenic faults at the site and the ductile nature of both the repository host rock and the salt units below the repository, the site-specific probability of large earthquakes is likely to be significantly less than the probability cited above. Therefore, a large movement on an existing large through-going fault within the controlled area at Davis Canyon is estimated to have less than 1 chance in 10,000 of occurring over 10,000 years. Because of the negligible probability of the initiating event, this scenario is not considered credible for the Davis Canyon site.

Scenario 6: Movement on a large fault within the repository

Using analyses similar to those described for scenario 5, a significant movement on an existing large fault intersecting the repository at the Davis Canyon site is estimated to have less than a 1 chance in 10,000 of occurring over 10,000 years. Therefore, this scenario is not applicable to the Davis Canyon site.

Scenario 7: Movement on a small fault inside the controlled area but outside the repository

An assessment of the probability of renewed movement on a small fault involves consideration of the location of known faults in the controlled area, the location of Quaternary faults, the level of seismicity in the geologic setting, and published recurrence statistics for the region of the site. Given the ductile nature of the host rock, the lack of Quaternary faults within the controlled area, and the relatively long recurrence times suggested by Algermissen et al. (1982), small-scale faulting is assumed to occur only in the brittle (nonsalt) stratigraphic units in the controlled area. On the basis of current data, estimates that small movements could occur within brittle rock units below the repository are on the order of 10^{-6} per year (range of 10^{-5} to 10^{-8} per year).

The evaluation of the expected range in median ground-water-travel times takes into account the possibility of fractures within the interbeds and the potential for these fractures to act as relatively high conductivity zones that extend to the accessible environment. If fault movement occurred, these travel times would be representative of the faulted pathways. However, the proportion of pathways with short travel times would still be considered small, and thus the range on travel time considered in the nominal case would not be altered. In addition, the time of ground-water travel through the interbeds may be only a small fraction of the total radionuclide-travel time, given the potential for the exceedingly long (million years) isolation time provided by the host rock. Consequently, renewed movements on small faults in the controlled area are not likely to result in significant releases. Hence, this scenario was not considered for the Davis Canyon site.

Scenario 8: Movement on a small fault within the repository

As in the case of scenario 7, an assessment of the probability of renewed movement on small faults involves consideration of the location of known faults in the controlled area, the location of Quaternary faults, the level of seismicity in the geologic setting, and published recurrence statistics for the region. Given the ductile nature of the host rock, the lack of Quaternary faults in the controlled area, and the relatively long recurrence times suggested by Algermissen et al. (1982), fault movement in the host rock is considered to have negligible probability, and therefore this scenario was not considered credible for the Davis Canyon site.

Scenario 9: Movement on a large fault outside the controlled area

At the Davis Canyon site, there may be evidence at Shay Graben that the magnitude of an earthquake could exceed the magnitudes observed historically. However, a full evaluation of the faults associated with Shay Graben has not been completed, and there is a possibility that observed fractures may be related to salt dissolution rather than seismogenic faults. Although a large event (magnitude greater than about 6.5) cannot be ruled out, no credible mechanisms are known that could significantly alter hydrologic conditions in the controlled area, even under the assumption that such an event occurs. Furthermore, any such fault movement would not affect the expected long isolation time provided by the ductile host rock. Section 6.3.1 of the EA for Davis Canyon (DOE, 1986a) discusses studies showing that changes in the vertical permeability outside the controlled area result in no significant changes to horizontal or vertical ground-water velocities from the repository to the accessible environment. Therefore, this scenario was not scored for the Davis Canyon site.

Scenario 10: Extrusive magmatic activity

There is no known Quaternary volcanism at the site. South Mountain (part of the LaSal Mountains) is the nearest volcanic stock, located at a distance of 43 km northeast of the site. This stock has been dated to be 23 to 26 million years old. The closest Quaternary volcanism, Specie Mesa in the San Miguel Mountains, is 127 km east of the site, outside the geologic setting of the Paradox Basin. Estimates of volcanism indicate an average probability for the contiguous United States of less than 10^{-8} per year (A. D. Little Inc., 1980.) In view of the above information, the probability of volcanism at this site in the next 10,000 years is less than 1 chance in 10,000. Therefore, this scenario is not considered to be credible at the Davis Canyon site.

Scenario 11: Intrusive magmatic activity

This scenario is considered not credible at the Davis Canyon site for the reasons given for scenario 10.

Scenario 12: Large-scale exploratory drilling

It is estimated that, during the past 25 years, 23 wells deeper than 700 m have been drilled in an area of approximately 1600 km^2 encompassing the Gibson Dome area and 7 wells within approximately 10 km of the Davis Canyon site (A. D. Little, Inc., 1980). This number extrapolates to a density on the order of six boreholes per square kilometer in 10,000 years. Considerations that take into account projected drilling practices and hydrocarbon usage lead to a conclusion of a finite probability of some drilling at the site that decreases to less than 1 chance in 10,000 of drilling 30 boreholes per square kilometer in 10,000 years (A. D. Little, Inc., 1980). This estimate does not take into account the presence of permanent markers at the site and societal records. Furthermore, the site does not provide any particular attraction over others in the surrounding area for resource development. Thus, the probability of drilling 30 or more boreholes per square kilometer at the Davis Canyon site in 10,000 years is judged to be less than 10^{-4}. However, the probability of drilling a smaller number of holes at the site may be larger. The base-case probability of any large-scale drilling at the site is judged to be 2×10^{-3}, with a range of 10^{-5} to 10^{-1}. Thirty boreholes per square kilometer in 10,000 years is used as an upper bound for this scenario.

There are two kinds of consequences to be considered: direct releases and indirect releases. Boreholes drilled very close to the waste package could result in a direct release if water brought to the surface is saturated with radionuclides. Since the repository would contain no significant amounts of water before drilling and since any flow in the borehole would tend to be downward rather than to the surface, the only source of such release would be the drilling fluids pumped to the surface. The EPA recommends that 200 m^3 of water per borehole be considered for this purpose (40 CFR Part 191, Appendix B). Using the isotope-concentration limits in Table D-1, the scenario leads to a direct release of about 6.4×10^{-10} of the EPA release limit per borehole. An uncertainty of at least two orders of magnitude should be attached to this value because of the uncertainty in concentration limits and other factors.

The indirect-release pathway has been evaluated for a borehole that is drilled through the repository and connects overlying transmissive units with underlying transmissive units. If the borehole is open and uncased, a maximum flow rate of about 10^5 m^3/yr is predicted (ONWI, 1985). This flow would continue until the borehole sealed itself because of creep in the salt units, resulting in a total volume of water of less than 10^5 m^3. There is, of course, considerable uncertainty in this result because it depends on hydraulic information that is not well known at present and the ability of the overlying aquifer to yield a large amount of water.

If the borehole fills with silt or other material from the overlying, unconsolidated units, the flow rate would be much lower (about 240 m^3/yr is predicted from the conductivity of the material in the borehole, 10^4 m/yr (ONWI, 1985)). At the same time, the material in the borehole could prevent closure because of salt creep. In this case, the flow could continue, which implies that 2.4×10^6 m^3 of water could flow through the borehole in 10,000 years and 2.2×10^7 m^3 in the next 90,000 years. Again, there is considerable uncertainty in these estimates. Not all of this water may be available to dissolve waste. The dissolution of salt at the repository horizon may be limited because the dissolution of salt units above this horizon would cause the water in the borehole to become saturated. Estimates indicate that dissolution would probably not extend to a distance of more than 10 m around the borehole (ONWI, 1985).

In order to provide upper-bound estimates, it is assumed that the hole is filled with silt. Using the total volumetric flow and scaling to provide a volumetric flow per 1000 MTHM, it was estimated that waste dissolution would result in a release of less than 1.2×10^{-4} of the EPA limits in 10,000 years and less than 4.9×10^{-5} in the next 90,000 years. These values would apply for each borehole.

The flow through the silted borehole is insufficient to perturb the velocities in the underlying receiving formations (ONWI, 1985). Thus, the estimated ground-water-travel times in this unit are unchanged from the values for the nominal case.

The repository area at Davis Canyon would be about 8 km^2. Therefore, about 240 boreholes would be drilled through the repository in this scenario. Of this number, less than 8 percent would provide indirect pathways for radionuclide transport and less than 1 percent would be close enough to the waste packages to allow a direct release to the surface. In the evaluation it was assumed that two boreholes allow a direct release. This amounts to a direct release of about 10^{-9} of the EPA limits in 10,000 years with an uncertainty of at least two orders of magnitude.

From area considerations, it is assumed that about 18 boreholes can provide indirect release pathways. The other boreholes would not be sufficiently close to waste packages to affect radionuclide migration. It is difficult to estimate releases in this case because the large delay due to radionuclide travel in the receiving aquifer would substantially reduce the inventories. However, the value of F can be calculated for comparison with the expected scenario. In this case, F has a nominal value of 2.2×10^{-3} for 10,000 years with an uncertainty of at least two orders of magnitude. For the period from 10,000 to 100,000 years, the nominal value of F is 8.8×10^{-4}. The predicted median radionuclide-travel time ranges between 230,000 and 430,000 years in either case.

The base-case score for the site is judged to be 9 for both performance measures. However, when taking into account the uncertainties because of the drilling and the somewhat reduced effectiveness of the concentration limits in constraining releases, the site is judged to have a high score of 10 and a low score of 6 for both performance measures.

Scenario 13: Small-scale exploratory drilling

Since the number of boreholes considered in this scenario is 10 times less than that for scenario 12, the consequences are reduced. The direct releases are clearly insignificant. For the indirect releases, the value of F is 2.2×10^{-4} for 10,000 years and 8.8×10^{-5} for the period 10,000 and 100,000 years. There are large uncertainties in these values because of the estimates for total water volume and waste solubility. The radionuclide-travel time is very long, on the order of a million years. Since the consequences are no greater than those for the nominal case, this scenario was not scored for the Davis Canyon site.

Scenario 14: Incomplete sealing of the shafts and the repository

The probability of incomplete sealing at the Davis Canyon site is very small. None of the units through which boreholes would be drilled would be difficult to seal. Although there is little experience with shaft sealing of the type contemplated for the repository, there is considerable experience with the sealing of boreholes in sedimentary rock. Furthermore, the creep of the salt would help in closing shafts and in sealing them. Therefore, the base-case probability of this scenario's resulting in any release is judged to be 10^{-4}, with a range of 10^{-5} to 10^{-3}.

Failure of the shaft and repository seals would permit water to fill the void space in the repository. For a shaft with a cross-sectional area of 30 m^2 and an average conductivity of 10 m/yr, the saturation of this void space could occur at a rate of about 300 m^3/yr. Thus, the quantity of water that could enter the repository through the sealed shafts could be considerably greater than the amount attributed to thermally induced brine migration. If the void space in the backfilled repository closes only to about 10 percent of the original excavated volume before saturation, the volume available for saturation with brine could be as much as 33,000 m^3 per 1000 MTHM. If this much brine were available to dissolve waste as a result of seal failure, the F value for the scenario would be about 1.3×10^{-4}. The range of uncertainty in this value is at least two orders of magnitude.

Water that fills the repository would not have an opportunity to carry away radionuclides because of the low permeability of the host salt. The natural gradient would not be sufficient to transport waste out through the failed seals. Thus, the travel time would still be very long, on the order of a million years.

With the exception of the possibly larger value of F in this scenario, the impacts are close to those for the nominal case. The increased possibility of waste dissolution, however, does influence the score. The base-case score is judged to be 10, with a range from 8 to 10, for the 10,000-year period, and 10, with a range from 7 to 10, for the period 10,000 to 100,000 years.

D.3 DEAF SMITH SITE

Scenario 1: Nominal case (expected conditions)

For the purpose of this analysis, it is assumed that a repository at the Deaf Smith site would be located entirely within a thick sequence of bedded salt in Unit 4 of the Lower San Andres Formation. The host salt bed lies about 800 m below the surface. It is assumed that the mined area occupies less than 30 percent of the underground repository area and that 70,000 MTHM of spent fuel would be distributed in about 16,000 waste packages (4.6 MTHM per package) over a total repository area of about 9 km^2.

Estimates of the brine migration induced in the salt show that 0.4 to 0.7 m^3 of high-magnesium brine would be available per waste package for corrosion and waste dissolution. Estimates of waste-package corrosion suggest that corrosion will be insufficient to cause any of the waste packages to fail under expected conditions. Even taking into account known uncertainties in corrosion rates, the waste-package lifetime is expected to exceed 10,000 years. Since all brine available from this migration process would be consumed in the corrosion of waste-package components, none would be available for waste dissolution. Other water may be available from seepage through transmissive interbeds. For example, below the host salt is a dolomite interbed that yielded a total of about 80 barrels of brine during 6 months of pumping. If seepage from this interbed into the repository could occur through fractures or anomalies in the salt, additional water would be available. Assuming the openings are backfilled with crushed salt and the creep of the salt results in a final void volume of 1 percent of the original mined openings, the maximum void volume available for water inflow would be less than 4000 m^3 per 1000 MTHM of waste. This quantity provides a reasonable upper bound to the amount of water that could seep into the repository openings. Assuming this amount of water, the waste-package lifetime would not be substantially different from that estimated for the Davis Canyon site (i.e., on the order of 2500 years).

Estimates of concentration limits for the waste-form constituents and the radionuclides are given in Table D-1. Particular values applicable at the site have a range similar to those considered for the Davis Canyon site. The estimated sums of ratios of isotope-concentration limits and EPA release limits are the same as those considered for the Davis Canyon site.

The Lower San Andres Formation is composed of relatively impermeable subunits. For example, the hydraulic conductivity of Unit 4 is probably much less than 10^{-6} m/yr. Other Permian confining units with equally poor conductivity lie above this formation. Very transmissive units that are located above these units are capable of yielding significant amounts of water. These transmissive units are separated from the salt host bed by about 500 m of confining strata. Underlying the host bed is nearly 900 m of lower Permian shale, mudstone, salt, and anhydrite strata with extremely low transmissivities. Below these beds are more transmissive units. Interbeds in the Permian section, such as the dolomite interbed immediately below the host salt, are transmissive in comparison with the salt. The gradients in the Permian section appear to be downward.

The Palo Duro Basin is relatively uncomplicated structurally, and modeling of this system indicates that the median time of ground-water travel to the accessible environment in the units that might receive radionuclides ranges between 25,000 and 500,000 years, depending on the distance to the accessible environment. If the distance to the accessible environment is 1 km, the estimated median ground-water-travel time ranges between 25,000 and 87,000 years. For a distance of 2 km, the median travel time is estimated to range between 45,000 and 170,000 years.

Retardation of radionuclide movement relative to ground-water movement is not expected to be high and is neglected altogether in the EA analyses (DOE, 1986b). In addition to travel time in the receiving transmissive units, the host salt and the confining layers between the host rock and the transmissive unit would contribute to a delay before release. More than a million years would be required for the diffusion of radionuclides through 20 m of salt. Depending on the receiving units, considerably more time would be required for transport to the transmissive unit. Therefore, it is possible for the radionuclide-travel time to be significantly longer than the ground-water-travel time estimated for the transmissive units.

The site characteristics and the resulting performance factors for the nominal case are summarized in Table D-2 for the first 10,000 years and in Table D-3 for 10,000 to 100,000 years. Again, the redundancy between the isolation provided by the concentration limits and the travel time for the nominal case can be readily seen.

The expected releases to the accessible environment are therefore expected to be insignificant. The base-case score for the first 10,000 years is judged to be 10. Because of uncertainties associated with the nearby interbeds, the low score is judged to be 8. These uncertainties become more important for releases beyond 10,000 years because the travel time in the interbeds may be comparable to a period from 10,000 to 100,000 years. Therefore, the base-case score for the second performance measure is judged to be 9, with the high and the low scores being 10 and 7, respectively.

Scenario 2: Unexpected features

Figure D-2 shows the possible range of unexpected features that could occur at the Deaf Smith site. As can be seen by comparison with Figure D-1, the features considered here are the same as those considered for the Davis Canyon site. This is not surprising in view of the fact that the unexpected features are those identified for generic salt beds. Accordingly, the probability of the scenario is judged to be very nearly the same for the Deaf Smith site as for the Davis Canyon site: .016 with a range from 0 to .1.

The score for the site is somewhat lower than that for the Davis Canyon, however, because the evaluation of the nominal case yielded a somewhat lower range of scores. That is, the unexpected features, such as undetected dissolution features in proximity to the repository, when combined with the wider range of expected conditions for the nominal case, result in a slightly lower score. The releases to the accessible environment are considered to be extremely low, and the base-case score assigned to the Deaf Smith site for this scenario is 8, with a low-to-high range of 5 to 10, for both performance measures.

UNEXPECTED FEATURES ↓	ROCK CHARACTERISTICS		GEOHYDROLOGY				GEOCHEMISTRY			
	SIGNIFICANT CHANGE IN HEAT CONDUCTION	SIGNIFICANT CHANGE IN MECHANICAL STRENGTH & DEFORMATION	CHANGE IN GROUND-WATER FLOW MECHANISM	NEW GROUND-WATER FLOW PATHS	SIGNIFICANT CHANGE IN HYDROLOGIC PROPERTIES	SIGNIFICANT CHANGE IN HYDRAULIC GRADIENT	SIGNIFICANT CHANGE IN SOLUBILITY, LEACH RATE, CORROSION, ETC., DUE TO TEMPERATURE INCREASE	CHANGE IN GROUND-WATER CHEMISTRY FROM NEW WATER SOURCE	LOW-GRADE METAMORPHISM OF ROCK, BACKFILL	CHANGE IN STATE FROM EQUILIBRIUM TO KINETIC
REPOSITORY-INDUCED SUBSIDENCE/UPLIFT		●	●	●	●					
UNDETECTED SMALL-SCALE FOLDING										
UNDETECTED LATERAL FACIES CHANGE	●	●	●	●	●				●	
UNDETECTED BRECCIA PIPES			●	●	●	●				●
UNDETECTED ZONES OF INCREASED POROSITY	●	●			●					
UNDETECTED BRINE POCKETS	●	●			●		●		●	
UNDETECTED PRESSURIZED GAS POCKETS		●								
UNDETECTED FRACTURED NON-SALT BEDS		●	●	●	●					
UNDETECTED SMALL-SCALE FAULTING			●		●					
OTHER	●	●	●	●	●	●	●		●	

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Figure D-2. Unexpected conditions at Deaf Smith County site.

Scenario 3: Repository-induced dissolution of the host rock

The dolomite interbed immediately beneath the host salt at the Deaf Smith site has been found to be somewhat transmissive and to contain brine. Rock fracturing due to repository heat or excavation could expose the overlying host rock to this brine; however, the brine is at or near saturation and would not be expected to have a significant effect on the overlying salt. The temperature coefficient of solubility for the NaCl-H_2O system is relatively small, so that even with the highest temperatures expected in the repository, dissolution at the interbed-salt interface would not be expected to be significant. Therefore, the consequences for this scenario are considered to be no more severe than those for the nominal case.

Scenario 4: Advance of a dissolution front

There is abundant evidence of the presence of active dissolution along the periphery and within the interior of the Palo Duro Basin. Peripheral dissolution of salt beds, including the repository horizon, has been identified along the western, northern, and eastern margins of the basin (166, 30, and 118 km from the site, respectively). Collapse features are usually associated with the zones of dissolution. The rates of dissolution for the eastern and the northern fronts have been estimated to be as high as 0.98 and 0.0008 m/yr, respectively; the rate of advance of the western front is believed to be less rapid. Interior dissolution may be occurring in the uppermost salt bed beneath the High Plains and is believed to be dissolving at a rate of less than 6.4×10^{-5} m/yr. At this rate of dissolution, the closest dissolution front would not reach the Deaf Smith site for more than 100,000 years.

In the event that local dissolution rates in the Palo Duro Basin increase by as much as 10 times, the increase would still not result in a zone of dissolution encroaching on the Deaf Smith site in less than 10,000 years. Thus, it was deemed unnecessary to evaluate further this scenario for the Deaf Smith site.

Scenario 5: Movement on a large fault inside the controlled area but outside the repository

There are no known faults that intersect the repository horizon in the controlled area. Although there is limited evidence of a fault in the controlled area that intersects Paleozoic units, displacements on this feature appear to terminate about 300 m below the repository level. While minor faults may exist and offset the basement strata, these faults do not appear to have the potential for generating a large earthquake. There are no known Quaternary faults anywhere in the geologic setting of the Deaf Smith site. Recurrence statistics from Nuttli and Herrmann (1978), Algermissen et al. (1982), Bernreuter et al. (1985), and the Electric Power Research Institute (1985), adjusted to the proposed size of the controlled area, suggest that the probability of Richter magnitudes greater than about 6 is on the order of 10^{-7} to 10^{-8} per year. Given the absence of known significant faults and the ductile nature of both the repository horizon and the salt units below the repository, the site-specific probability of large earthquakes is likely to be significantly less than 10^{-7} to 10^{-8} per year. Therefore, significant movement on an existing large through-going fault in the controlled area at the Deaf Smith site is estimated to have less than 1 chance in 10,000 of occurring over 10,000 years, and hence this scenario is not considered credible for the Deaf Smith site.

Scenario 6: Movement on a large fault within the repository

Similar reasoning as that for scenario 6 led to the judgment that the probability of significant movement on an existing through-going fault intersecting the repository at the Deaf Smith site is less than 1 chance in 10,000 over 10,000 years. Therefore, this scenario is not considered applicable to the Deaf Smith site.

Scenario 7: Movement on a small fault inside the controlled area but outside the repository

The evaluation for the Deaf Smith site is similar to that for the Davis Canyon site, with two small differences. First, no Quaternary faults are known to exist anywhere in the geologic setting, and, second, earthquake-occurrence rates in the vicinity of the Deaf Smith site are slightly lower. Given the ductile nature of the host rock and the low earthquake-occurrence rates, the probability of faults in the controlled area (i.e., small movements within the brittle interbed units) is estimated to be on the order of 10^{-7} per year, with a range of 10^{-6} to 10^{-8} per year.

The evaluation of potential consequences considered arguments similar to those stated for Davis Canyon. That is, the ground-water-travel times for the interbed zones that are considered as fracture pathways and the exceedingly long (million years) isolation time expected to be provided by the host rock would overwhelm small changes in radionuclide-travel times in units below the host rock. Thus, renewed movements on small faults in the controlled area are not likely to result in significant releases, and this scenario is therefore not considered to be of significance at the Deaf Smith site.

Scenario 8: Movement on a small fault within the repository

The evaluation for the Deaf Smith site is similar to that for the Davis Canyon site, with two small differences. First, no Quaternary faults are known to exist anywhere in the geologic setting, and, second, earthquake-occurrence rates in the vicinity of the Deaf Smith site are slightly lower. Given the ductile nature of the host rock and the low earthquake-occurrence rates, this scenario was eliminated on the basis of negligible probability.

Scenario 9: Movement on a large fault outside the controlled area

There are no Quaternary faults in the geologic setting of the Deaf Smith site; thus, there is no direct indication that large (magnitude greater than about 6.5) earthquakes are possible. In addition, there have been no credible mechanisms identified (i.e., those due to large faulting outside the controlled area) that could significantly alter hydrologic conditions in the controlled area if such an earthquake were to occur. Similarly, it is not likely that the long isolation time expected to be provided by the ductile host rock would be affected. Section 6.4.2 of the EA (DOE, 1986b) cites studies showing that credible changes in hydraulic heads in recharge zones would result in no significant changes in ground-water-travel times. Because any credible events would have no perceived consequences, this scenario was not scored for the Deaf Smith site.

Scenario 10: Extrusive magmatic activity

The nearest igneous activity to the site during Quaternary time occurred about 160 km from the site. The only area in the region that has experienced volcanic activity since Early Paleozoic time is in northeastern New Mexico (Stone & Webster Engineering Corporation, 1983), outside the geologic setting of the Palo Duro Basin. No igneous activity has occurred in the site vicinity for more than 500 million years. Therefore, this scenario is not considered to be credible for the Deaf Smith site.

Scenario 11: Intrusive magmatic activity

This scenario is not considered to be credible at the Deaf Smith site for the reasons given for scenario 10.

Scenario 12: Large-scale exploratory drilling

It is estimated that the Palo Duro Basin contains about 550 wells in an area of more than 30,000 km^2 (A. D. Little Inc., 1980), but none of these wells is within 10 km of the Deaf Smith site. Projections of future drilling based on this information lead to a finite probability of some drilling at the site that decreases to less than 1 chance in 10,000 of drilling 30 boreholes per square kilometer in 10,000 years (A. D. Little, Inc., 1980). Again, these evaluations did not take into account passive institutional controls at the site. Therefore, the probability of drilling 30 or more boreholes per square kilometer in 10,000 years is judged to be less than 10^{-4}. However, the probability of drilling a smaller number of holes at the site may be larger. The base-case annual probability of any large-scale drilling at this site is judged to be 2×10^{-3}, with a range of 10^{-5} to 10^{-1}. Thirty boreholes per square kilometer in 10,000 years is used as an upper bound for this scenario.

To estimate consequences, the considerations discussed for the Davis Canyon site can be applied. As the expected repository area is about 9 km^2, 270 boreholes are considered in this scenario. This implies that only 3 of the boreholes would lead to direct releases and only 22 to indirect releases. The direct-release pathways would lead to a release at the surface of less than 2×10^{-9} of the EPA limits.

Calculations for the indirect pathway again show downward flow through the boreholes to the receiving aquifer. The silted-borehole estimate (10^4-m/yr conductivity) yields a flow-rate estimate of about 200 m^3/yr, or about 2×10^6 m^3 in 10,000 years and about 1.8×10^7 m^3 in the next 90,000 years. Scaling this volume to get a volumetric flow per 1000 MTMH of waste gives 2.8×10^4 and 2.5×10^5 m^3 per 1000 MTHM, respectively. The value of F in this case would be 2.3×10^{-3} in the first 10,000 years and 8.8×10^{-4} in the next 90,000 years. Again there are uncertainties of at least two orders of magnitude in these estimates.

The time of ground-water travel in the receiving unit is not expected to be affected by the small flow through the borehole (ONWI, 1985). Thus, the median radionuclide-travel time is estimated to range between 45,000 and 170,000 years.

From the performance factors and the associated uncertainties, the base-case score for this scenario is judged to be 9, with a low-to-high range of 6 to 10, for both performance measures.

Scenario 13: Small-scale exploratory drilling

The value of F for the Deaf Smith site in this case is 2.3×10^{-4} for the first 10,000 years and 8.8×10^{-5} for the next 90,000 years. Large uncertainties of two orders of magnitude or more accompany these values. Nevertheless, the consequences of this scenario would not exceed those of the nominal case, and therefore the Deaf Smith site was not scored against this scenario.

Scenario 14: Incomplete sealing of the shafts and the repository

The failure probability for the shaft and repository seals is very low for the Deaf Smith site. There is considerable experience drilling through the Ogallala aquifer and the underlying units and in sealing the borings. The base-case probability that this scenario might affect repository performance in 10,000 years is judged to be 2×10^{-4} with a range of 2×10^{-5} to 2×10^{-3}. This probability is somewhat greater than that for the Davis Canyon site because the interbeds in the Permian section might make the sealing of shafts and boreholes more difficult.

Incomplete sealing of the shafts and the repository could result in flow rates into the repository of 300 m^3/yr. Thus, more water than estimated in the nominal case may be available for the dissolution of the waste. Assuming that creep closure would reduce the void volume of the backfilled repository to about 10 percent of the originally excavated volume, the maximum amount of water that can enter the repository is found to be about 40,000 m^3 per 1000 MTHM of waste. This volume is 10 times that considered in the nominal case and results in an F value of about 1.5×10^{-4}. The travel time would not be different from the nominal case because there is no driving force to move water away from the repository through the seals; thus, diffusive transport through the salt is still expected to control the radionuclide-travel time.

Taking into account the uncertainties associated with this scenario, the base-case score is judged to be 10, with a low score of 7 for the first performance measure, and a base-case score of 9, with a low-to-high range of 6 to 10, for the second performance measure.

D.4 RICHTON DOME SITE

Scenario 1: Nominal case (expected conditions)

For this analysis, it is assumed that a repository at Richton Dome would be located entirely within the salt contained in the dome. The dome is composed of an extensive salt stock overlain with about 50 m of gypsum caprock. The top of the dome is at a depth of about 150 to 300 m and is overlain above the caprock by a fresh-water aquifer system. It is assumed that the repository would be constructed about 650 m below the land surface, at least 300 m into the salt stock. It is assumed that the mined area would occupy less than 30 percent of the repository area and that the 70,000 MTHM of spent fuel would be distributed in about 16,000 waste packages (4.6 MTHM per package) over a total repository area of 8 km^2. The minimum distance between the repository and the flank of the dome would be more than 240 m.

Estimates of brine migration induced in the salt show 0.01 to 0.1 m^3 of low-magnesium brine per waste package, which is assumed to be available for waste-package corrosion and waste dissolution. Estimates of waste-package lifetime, assuming these volumes and uniform corrosion, suggest that the waste packages are expected to last much longer than 10,000 years. Although there is no site-specific evidence for continuous connections such as shear zones in the dome, these could exist and provide a low-permeability conduit for ground-water influx into the repository if they were to connect to the overlying nonsalt formations. If the void volume of the backfill is similar to that of the Davis Canyon site, the maximum volume of water that could seep into the repository through any such connection and be available for dissolution is less than 3300 m^3 per 1000 MTHM. If this amount of water is available, the estimated waste-package lifetime could decrease to 4800 years.

The concentration limits used in the EA analyses (DOE, 1986c) are given in Table D-1. Again, particular values at the site could vary by one order of magnitude above and three or more orders of magnitude below these values.

The geohydrology surrounding the Richton Dome is sufficiently complex and difficult to model that very little credit can be taken at present for any favorable features of this system. However, the travel time of radionuclides from the repository through the salt buffer zone to the dome margin is expected to be very long even without any delay in the surrounding units. For example, travel-time estimates based on diffusion through the salt stock exceed 10 million years. For comparison, the transport was evaluated with a model based on Darcy flow and advective transport; the median travel time was calculated to be 35 million years. Retardation was neglected in these estimates.

The site characteristics and performance factors for the expected scenario are summarized in Tables D-2 and D-3. Again, the redundancy between the isolation provided by the concentration limits and the travel time is significant. Releases to the accessible environment are therefore expected to be insignificant.

Taking into account uncertainties in the site parameters, the base-case score for the Richton Dome is judged to be 10 and the low score 8 for both performance measures.

Scenario 2: Unexpected features

Figure D-3 indicates the possible range of unexpected features that could occur at the Richton Dome site. Many of the unexpected features considered for the bedded-salt sites are applicable to salt domes. An additional

UNEXPECTED FEATURES ↓	ROCK CHARACTERISTICS		GEOHYDROLOGY				GEOCHEMISTRY			
	SIGNIFICANT CHANGE IN HEAT CONDUCTION	SIGNIFICANT CHANGE IN MECHANICAL STRENGTH & DEFORMATION	CHANGE IN GROUND-WATER FLOW MECHANISM	NEW GROUND-WATER FLOW PATHS	SIGNIFICANT CHANGE IN HYDROLOGIC PROPERTIES	SIGNIFICANT CHANGE IN HYDRAULIC GRADIENT	SIGNIFICANT CHANGE IN SOLUBILITY, LEACH RATE, CORROSION, ETC., DUE TO TEMPERATURE INCREASE	CHANGE IN GROUND-WATER CHEMISTRY FROM NEW WATER SOURCE	LOW-GRADE METAMORPHISM OF ROCK, BACKFILL	CHANGE IN STATE FROM EQUILIBRIUM TO KINETIC
REPOSITORY-INDUCED NONSALT		●	●	●	●	●				
UNDETECTED SMALL-SCALE FOLDING										
UNDETECTED VERTICAL NONSALT INTERBEDS			●	●	●	●				
UNDETECTED VARIATION IN SALT QUALITY										
UNDETECTED ZONES OF INCREASED POROSITY	●	●			●					
UNDETECTED BRINE POCKETS	●	●					●			
UNDETECTED PRESSURIZED GAS POCKETS		●								
OTHER	●	●	●	●	●	●	●			

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Figure D-3. Unexpected features at the Richton Dome site.

possibility includes anomalous zones in the dome, such as shear zones or bands of nonsalt rock that separate the different lobes and folds in the dome. These features may be continuous or discontinuous and could exert extreme effects on the flow pathways and conditions associated with the dome interior.

The panel also considered potential impacts due to small-scale folding or variations in the quality of salt in the dome stock. The panel concluded that such features would not have significant impacts on any of the factors affecting performance.

The effects of other unexpected features, such as undetected dissolution features or caprock fracturing that could lead to enhanced dissolution, are not considered likely to lead to significant impacts on expected repository performance. Therefore, the base-case score is judged to be 9, with a low-to-high range from 6 to 10, for both performance measures. The base-case probability that unexpected features could affect performance is estimated to be .013, with a range from 0 to .1.

Scenario 3: Repository-induced dissolution of the host rock

Previous rates of dissolution during the formation of the Richton Dome and for subsequent phases of dissolution during geologic time have been estimated to be between 3 and 5 cm per 1000 years. These estimates are based on the thickness of the caprock, the abundance of anhydrite in the salt stock, an assumption regarding the commencement of dissolution, and the concept that the caprock was formed from the residue of anhydrite after the dissolution of the salt stock. On this basis, it would take on the order of 5 million years for a zone of dissolution migrating from the flank of the dome to intersect the repository. Even if it is assumed that the dissolution-rate estimates were low by two orders of magnitude and that a much higher dissolution rate could be maintained in spite of increasingly restrictive circulation, the zoneof dissolution would not reach the repository for at least 50,000 years. The caprock of Richton Dome shows evidence of fractures that subsequently have been filled with gypsum, thereby limiting the flow of water to and from the salt stock. Therefore, any dissolution of the salt resulting from the thermally induced fracturing of the caprock or sheath would proceed at rates comparable to the historical average and would likely be self-limiting. As a result, the scenario does not have consequences different from the nominal case for the Richton Dome site.

Scenario 4: Advance of a dissolution front

The advance of a dissolution front at the Richton Dome site is considered to have a negligible probability of occurrence, and therefore the site was not scored for this scenario.

Scenario 5: Movement on a large fault inside the controlled area but outside the repository

No Quaternary faults are known to occur in the controlled area at the Richton Dome site. There are no known Quaternary faults in the geologic setting, and the closest known earthquake occurred 75 km from the dome. Recurrence statistics from Nuttli and Herrmann (1978), Algermissen et al. (1982), the Lawrence Livermore National Laboratory (1985), and the Electric

Power Research Institute (1985), adjusted to the size of the controlled area, suggest that the probability of magnitudes greater than about 6 is on the order of 10^{-7} to 10^{-8} per year. Given the absence of known significant faults and the ductile nature of the host rock, the site-specific probability of large earthquakes is significantly less than that indicated above. Therefore, the probability of significant movement on an existing large through-going fault within the controlled area at the Richton Dome site is estimated to be less than 1 chance in 10,000 over 10,000 years. Because of the negligible initiating-event probability, this scenario is judged not credible for the Richton Dome site.

Scenario 6: Movement on a large fault within the repository

From the analysis for scenario 5, the probability of significant movement on an existing large fault intersecting the repository at the Richton Dome is estimated to be less than 1 chance in 10,000 over 10,000 years. Therefore, this scenario is not credible for the Richton Dome site.

Scenario 7: Movement on a small fault inside the controlled area but outside the repository

No faults are known to occur in the controlled area at the Richton Dome site. There are no known Quaternary faults in the geologic setting, and the closest known earthquake occurred 75 km away. Earthquake-recurrence statistics for this region of the United States suggest that the probability of earthquakes for areas of the size of the dome is exceedingly low. Given the fact that the rock unit in the controlled area is comprised of ductile salt, the probability of faulting is likely to be significantly less than 10^{-8} per year for small-scale faulting anywhere in the controlled area. Because of the negligible initiating-event probability, this scenario is judged not credible at the Richton Dome site.

Scenario 8: Movement on a small fault within the repository

For the reasons explained under scenario 7, the probability of small-scale faulting anywhere in the controlled area is likely to be significantly less than 10^{-8} per year. Consequently, this scenario is judged not credible at the Richton Dome site.

Scenario 9: Movement on a large fault outside the controlled area

At the Richton Dome, there are no Quaternary faults within the geologic setting, and the likelihood of any earthquakes near the site is extremely small. No credible mechanisms have been identified by which faulting outside the controlled area could occur and significantly alter hydrologic conditions within the controlled area. Thus, this scenario is judged not credible for the Richton Dome site.

Scenario 10: Extrusive magmatic activity

There is no known Quaternary volcanism at the site. The nearest known igneous body, Jackson Dome, is 160 km northwest of the Richton Dome site and appears to be of Cretaceous age (Bornhauser, 1958). Therefore, this scenario is judged not credible for the Richton Dome.

Scenario 11: Intrusive magmatic activity

This scenario is judged not credible at the Richton Dome site for the reasons given under scenario 10.

Scenario 12: Large-scale exploratory drilling

There have been at least 9 borings into the salt stock and 31 into the caprock at the Richton Dome. Also, there have been 39 borings within a radius of 2 km and 85 within a radius of 8 km (A. D. Little, Inc., 1980). Not all of these extend to the depth of the repository horizon. It is estimated that the frequency of boreholes more than 650 m deep is less than 0.3 per square kilometer. Assuming these have been drilled during the past 40 years leads to an extrapolation of less than 70 boreholes per square kilometer in 10,000 years. However, corrections to take into account the propensity to drill outside the dome and at the dome margin lead to a projection, based on past experience, of about 25 boreholes per square kilometer in 10,000 years. Projections of hydrocarbon usage and exploration into the future lead to a further adjustment in this estimate and a conclusion that the probability of drilling 30 boreholes per square kilometer of the repository in 10,000 years is less than .0001 (A. D. Little, Inc., 1980). Again, these considerations do not take into account the passive institutional controls that would be effective at the site. However, the probability of drilling a smaller number of holes at the site may be larger. The probability of any large-scale drilling is estimated to be the about same as that for drilling at the two bedded-salt sites; that is, the base-case annual probability is estimated to be 2.0×10^{-3}, with a range of 10^{-3} to 10^{-1}. Thirty boreholes per square kilometer in 10,000 years is used as the upper bound for this scenario.

The expected repository area is 8 km^2, so that 240 boreholes are considered in the scenario. It is estimated that only about 2 of these boreholes could lead to a direct release and 18 could lead to an indirect release. Assuming 200 m^3 of water per hole in the direct release, the release is predicted to be about 10^{-9} of the EPA release limits in 10,000 years.

No calculation of the indirect pathway can be found in the literature for the Richton Dome site. A limited analysis was conducted for the Cypress Creek Dome, which involves the same hydrologic units as the Richton Dome site (memorandum from A. M. Monti and S. K. Gupta, Office of Nuclear Waste Isolation, 1984). The results of the calculated flow rates, salt dissolution, and borehole closure due to salt creep give values that are comparable to those for Davis Canyon and Deaf Smith. Therefore, the flow rate for the boreholes at Richton Dome is assumed to be the same as that for Davis Canyon. The F values are assumed to be about 2.3×10^{-3} for 10,000 years and 8.8×10^{-4} for the period between 10,000 and 100,000 years. There is large uncertainty in these values.

The travel-time estimates for the nominal case are based on water movement through the host salt. In this scenario, the dome is breached. The travel time outside the dome is difficult to predict. Some analyses give travel times exceeding 10,000 years to the accessible environment; however, the present conceptual models do not preclude a median travel time that is less than 10,000 years.

The uncertainties in the case of drilling at the Richton Dome are somewhat larger than for the bedded-salt sites. That is, while the travel time is judged to be relatively unchanged from the nominal case for the bedded-salt sites, the change would be very important at the dome site. In the nominal case, credit is taken for the time of travel through the dome only. However, in this scenario the dome is breached to the adjacent sedimentary strata by the drilling. Therefore, little if any credit can be taken for the travel time outside the dome since the controlled area is chosen to be the boundary of the dome. Therefore, reliance on the travel time to provide a degree of isolation cannot be assumed in this case. As a result, the base-case score for the Richton Dome site for this scenario is judged to be 8, with a low-to-high range of 4 to 10, for both performance measures.

Scenario 13: Small-scale exploratory drilling

The value of F in this case is taken to be about 2.3×10^{-4} for the 10,000-year period and 8.8×10^{-5} for the period 10,000 to 100,000 years. In view of the negligible releases through the borehole, it was concluded that the Richton Dome site should not be scored for this scenario.

Scenario 14: Incomplete sealing of the shafts and the repository

The failure of shaft and repository seals has a somewhat greater probability for the salt-dome site than for the bedded-salt sites, on the basis of experience in mining in the Gulf Coast domes. The probability in 10,000 years is judged to be 5×10^{-4}, with a range of 5×10^{-5} to 5×10^{-3}.

Using considerations analogous to those for the bedded-salt sites, the F factor is estimated to be about 1.3×10^{-4}, with an uncertainty of at least two orders of magnitude. Radionuclide-travel times are not significantly affected in this scenario because there is no driving force to move water from the repository through these seals. The base-case score for Richton Dome is therefore judged to be 10, and the low score 7, for both performance measures.

D.5 HANFORD SITE

Scenario 1: Nominal case (expected conditions)

For the purpose of this analysis, it is assumed that the repository at the Hanford site would be constructed entirely within the dense interior of the Cohassett basalt flow. This flow has a dense interior that is about 70 m thick at the reference repository location and is located at a depth of more than 900 m below the surface. It is assumed that the 70,000 MTHM of spent fuel would be distributed in 40,000 waste packages (1.8 MTHM per package) over a total repository area of about 8 km^2.

Estimates of waste-package performance, based on quiescent, saturated conditions and uniform corrosion, indicate a lifetime of about 6000 years. The expected range in container lifetime is from 4500 to 8500 years.

The volume of water available for waste dissolution depends on the saturated volume in the repository and the replacement rate of this water. The void volume (assuming backfilling to about 30 percent void volume of the openings) is about 100,000 m^3 per 1000 MTHM. The replacement rate depends on the flux through the host rock, which depends, in turn, on the hydraulic gradient and the conductivity of the rock. It is assumed that the gradient is vertically upward with a value of about 0.001. The horizontal conductivity of the intact basalt in the host rock is probably less than 10^{-5} m/yr, but the vertical conductivity of the unit could be greater by four orders of magnitude or more because of fractures through the dense interior that may not be entirely filled with secondary minerals. This range in conductivity results in a flux between 10^{-8} and about 10^{-4} m^3/m^2-yr. Assuming an effective area of 30 m^2 per waste package, the volume of water that moves through the repository is less than 20,000 m^3 per 1000 MTHM in 10,000 years. Thus, the amount of water available for waste dissolution in 10,000 years is estimated to be between 100,000 and 120,000 m^3 per 1000 MTHM. In the 90,000-year period between 10,000 and 100,000 years after closure, the total volume of water moving through the repository corresponds to about 9 times the volume moving through in 10,000 years, or between 18 and 180,000 m^3 per 1000 MTHM of waste.

The concentration limits used in the EA analysis (DOE, 1986d) are given in Table D-1. These values represent upper bounds to element solubilities calculated from thermodynamic data for Grand Ronde waters and oxidizing conditions. Applicable values for particular radioelements could be smaller by four orders of magnitude or more. The sum of the ratios of the associated isotope solubilities and the EPA release limits are also given in Table D-1. These ratios can be combined with the volume of ground water that could reach the waste to estimate the performance factor F. This factor would provide an upper bound to the cumulative releases from the engineered-barrier system because the release is limited by diffusion rather than leach solubility. That is, the waste-package system includes a layer of bentonite packing material around the container that constrains the release from the waste package; the estimates on the concentration limits neglect any credit for this diffusion layer.

The ground-water-travel time has been calculated with a set of conceptual models for the geohydrologic system. The deep basalts at the Hanford site form a layered sequence consisting of dense, fractured basalt flow interiors overlain by brecciated and vesicular flow tops. The conductivity of the flow interior is assumed to be lower than that of the flow tops because of the smaller volume of interconnected fracture and pore space. This permeability contrast promotes horizontal ground-water flow in the flow tops and essentially vertical leakage through the flow interiors.

Conceptual models that have been used to calculate the ground-water-travel time range between an essentially confined ground-water flow system with low vertical leakage across the dense interiors to a system with relatively high vertical leakage across flow interiors and along discrete structural discontinuities. The calculated median times of ground-water travel range from 22,000 to 83,000 years for pre-waste-emplacement conditions. These travel times are probably indicative of the post-waste-emplacement values as well.

Available sorption data indicate that the retardation factors for the basalt flow interior and the flow top generally range between 200 and 200,000 for the critical radionuclides. An exception is technetium, which may have a retardation factor close to zero under some conditions. Although this situation is unlikely because of the reducing conditions in the deep units at the Hanford site, there is a possibility that the retardation of the key radionuclide technetium-99 would be negligible.

The time of ground-water travel and the retardation factors give an estimated radionuclide-travel time in the ground-water system that ranges between 22,000 and 1.6×10^{10} years, depending on the sorption factor. This estimate neglects any delay between the time when waste dissolution occurs within the waste package and the time when the waste is captured by the moving ground water in the rock.

Pertinent site characteristics and associated performance factors are summarized in Tables D-2 and D-3. As can be seen, there is a wide range of uncertainty in site performance. Waste isolation at the Hanford site is particularly dependent on the geochemistry. The evidence suggests that both the concentration limits and the retardation factors are favorable due to the geochemistry.

These performance factors would result in expected releases that range between very small and insignificant. Taking into account the wide range of uncertainty in expected repository performance, particularly for travel times shorter than 100,000 years, the base-case score is judged to be 8, with a high score of 10 and a low score of 4, for the first performance measure. Because the range of the median time of ground-water travel is less than 100,000 years, the base-case score for the second performance measure is judged to be 7, with a low-to-high range of 4 to 10.

Scenario 2: Unexpected features

Figure D-4 shows the possible range of unexpected features that the panel considered for the Hanford site as well as the various effects they could exert. Among them are subsidence and uplift, which were also considered for the salt sites. Another possible feature is a feeder dike that originally provided the source of magma for an overlying flow. Such a feature, if it occurs within the controlled area, could provide a barrier that could affect the ground-water flow important to waste isolation.

Among the unexpected features are profuse internal structures within the host rock, including vesicular zones, pillow zones, and other features that could influence the thermal and mechanical strength properties of the basalt and could affect the geohydrologic regime. Such structures were considered to some extent in the evaluation of the expected conditions, but extreme variations in these features were not taken into account under the expected conditions. For example, the ground-water-flow conditions could be so extreme that modeling based on an equivalent Darcy-flow representation, used in the nominal case, might not be adequate. Similarly, flow pinch out, vertical fracture zones, or a major fault, which were considered in the scenario for the expected conditions, could result in extreme conditions not evaluated in that case. Unexpected features that could, for example, change the oxidation-

UNEXPECTED FEATURES ↓	ROCK CHARACTERISTICS		GEOHYDROLOGY				GEOCHEMISTRY			
	SIGNIFICANT CHANGE IN HEAT CONDUCTION	SIGNIFICANT CHANGE IN MECHANICAL STRENGTH & DEFORMATION	CHANGE IN GROUND-WATER FLOW MECHANISM	NEW GROUND-WATER FLOW PATHS	SIGNIFICANT CHANGE IN HYDROLOGIC PROPERTIES	SIGNIFICANT CHANGE IN HYDRAULIC GRADIENT	SIGNIFICANT CHANGE IN SOLUBILITY, LEACH RATE, CORROSION, ETC., DUE TO TEMPERATURE INCREASE	CHANGE IN GROUND-WATER CHEMISTRY FROM NEW WATER SOURCE	LOW-GRADE METAMORPHISM OF ROCK, BACKFILL	CHANGE IN STATE FROM EQUILIBRIUM TO KINETIC
REPOSITORY-INDUCED SUBSIDENCE/UPLIFT		●	●	●	●			●		
UNDETECTED FEEDER DIKES					●					
UNDETECTED PROFUSE INTERNAL FLOW STRUCTURE	●	●	●	●	●		●			
UNDETECTED FLOW PINCHOUT					●					
UNDETECTED VERTICAL FRACTURE ZONES (< 1 m)		●		●	●	●		●		
UNDETECTED MAJOR FAULT				●	●			●		
OTHER	●	●	●	●	●	●	●	●		

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Figure D-4. Unexpected features at the Hanford site.

reduction conditions to the extent that the reducing potential is less than expected could have an adverse effect on repository performance as shown in Figure D-4.

The probability that these extreme conditions might arise at the Hanford site is small. That is, the range of expected conditions contains most of the uncertainties considered in the evaluation. The base-case probability that unexpected features exist and would lead to significant impacts on the expected performance of the repository is judged to be .024, with a range from 0 to .25.

It is the judgment of the panel that releases might be increased by as much as 10 times from the nominal case because of increased solubility and lower retardation of certain key radionuclides, such as technetium. The base-case score for this scenario is judged to be 6, with a low-to-high range from 2 to 10, for both performance measures. The wide range reflects the considerable uncertainty in the existence of unexpected features and their impact on the expected performance of the repository.

<u>Scenario 3: Repository-induced dissolution of the host rock</u>

Because this scenario applies only to relatively soluble rocks, it is not considered credible at the Hanford site.

<u>Scenario 4: Advance of a dissolution front</u>

Because this scenario applies only to relatively soluble rocks, it is not considered credible at the Hanford site.

<u>Scenario 5: Movement on a large fault inside the controlled area but outside the repository</u>

From the low long-term average rate of deformation of the central Columbia Plateau and the available information about microseismic activity in the area, the EA for the Hanford site (DOE, 1986d) concludes that tectonic conditions at the site are expected to be favorable. That is, the EA concludes that there is no evidence that expected tectonic processes would have more than 1 chance in 10,000 over the first 10,000 years of leading to releases to the accessible environment. Unexpected disruptions, such as a movement on a large fault inside the controlled area, were not evaluated in the EA because there is no evidence of such a feature at the site and no consequence analyses for such disruptive-event scenarios have been performed. The nearest Quaternary faults are on Gable Mountain, about 8 km north of the site, and at Finley Quarry along the Rattlesnake-Wallula Alignment (RAW), about 40 km to the southeast. Extensive mapping and geophysical surveys suggest that the synclinal region where the site is located would be associated with fewer large faults than are anticlinal ridges. At the same time, there are several possible interpretations of relatively small geophysical anomalies within the controlled area, along with very minor amounts of microseismicity, that are consistent with some fault movement within the basalt sequence. Recurrence statistics (Woodward-Clyde, 1980; Algermissen et al., 1982; Washington Public Power Supply System, 1982), adjusted to the size of the controlled area, suggest that the probability of earthquakes with a magnitude greater than about 6 is on the order of 10^{-5} to

10^{-6} per year. Specific probabilities estimated for the RAW are on the order of 2 x 10^{-5} for a magnitude of 6.5 (NRC, 1982). In view of the observation that synclines are not generally associated with large faults, the site-specific probability of earthquakes with a magnitude greater than about 6 is likely to be significantly less than 10^{-6} per year. However,in order to consider even low-probability events that might have significant consequences, it is conservatively assumed for this scenario that such a fault does exist at the site and may experience renewed movement.

In comparison with the expected conditions, this scenario has an increased likelihood of pathways associated with relatively fast times of ground-water travel. Since the fault does not intersect the repository, the ground-water-travel time in the dense interior above the repository, the flux through the repository, and waste-package integrity are not likely to be affected. Nevertheless, the overall travel time is likely to be reduced, and the estimate for this scenario is that the median time of ground-water travel from the disturbed zone to the accessible environment for the fault-dominated pathway could be about 10,000 years. The uncertainty in the median travel time is represented by a range of 1000 to 50,000 years. This range is estimated on the basis of the evaluations in the EA as well as by considering the median time of travel through the undisturbed host rock and through the flow top until the relatively highly permeable fault is encountered. Compared with the expected conditions (range of 22,000 to 83,000 years for the median time of ground-water travel), where appreciable variance in the ratio between the vertical and the horizontal hydraulic conductivities of dense interiors has an important influence on the travel-time range, the overall decrease in the ground-water-travel time is likely to be less than tenfold. The only other performance factor that may be altered is the retardation, which may be reduced because of kinetic effects for the fault pathway if the rate of radionuclide transport is relatively rapid.

The base-case probability of this scenario is estimated to be .0032 over 10,000 years with a range of .01 to .00001. Considering the estimated affects on the performance factors, the base-case scores for both performance measures are judged to be 7, with a low-to-high range of 3 to 10. These scores are somewhat lower than those for the nominal case, reflecting the potential for shorter radionuclide-travel times.

<u>Scenario 6: Movement on a large fault within the repository</u>

From the analysis for scenario 5, the probability of magnitudes greater than about 6 is estimated to be less than about 10^{-6} per year for movement on a large through-going fault within the controlled area at the Hanford site. Two factors need to be considered in estimating whether or not such an event would intersect the repository. The first factor is the size of the repository area, which is smaller than the controlled area. For this analysis it is assumed that the decrease in area will lower the probability by at least tenfold. The second factor involves the consideration that, if a large through-going fault were encountered during construction, no waste would be emplaced in such a zone. These institutional controls are likely to significantly lower the probability that a waste package would be sheared because it was emplaced in a large fault zone that subsequently experienced movement. Therefore, it is highly unlikely that waste packages would be damaged by movement on such a fault.

Taking the above considerations into account, the site-specific probability of movement on a large fault that intersects the repository area is likely to be less than about 10^{-7} per year. Because the existence of a large through-going fault cannot be ruled out without site-characterization data, it is conservatively assumed for this scenario that such a feature may exist and experience renewed movement.

In contrast to the discussion for scenario 5, movement on a large through-going fault that intersects the repository may reduce the containment capability of the dense interior of the host rock for that pathway. One consideration is whether such a feature would also serve as a vertical pathway before renewed movement. As discussed for the expected conditions, there is some uncertainty about the extent of permeable, vertical fractures within the flow interiors. Renewed movement on a large fault may increase the likelihood that there may be pathways associated with relatively fast travel times. The estimate for this scenario is that the range in the median of the ground-water-travel time is 1000 years to 20,000 years. As for scenario 4, the lower end of this range represents the travel paths contained within the relatively permeable fractured zone. The upper end of the range takes into account pathways in the undisturbed rock units. Uncertainty in the retardation factors is likely to increase.

Because such a fault would connect confined aquifers above and below the repository, the volume of ground-water flow through the repository may be altered. As discussed under the nominal case, there is a wide range in ground-water-flux values, depending on the assumed hydraulic parameters (e.g., hydraulic conductivity) for the flow interiors. If the pathway with the relatively high conductivity exists, the flux values considered for the nominal case may not be appropriate for the fault-controlled pathway: the lower flux values may be increased for the fault-controlled pathway, perhaps by two orders to magnitude. The higher flux values, which were estimated under the assumption that permeable vertical fractures may exist in portions of the host rock, are assumed to be applicable for this scenario. Flux through the undisturbed portion of the repository would be similar to that assumed for the nominal case. The early loss of waste packages through shearing may not be significant because the radionuclide-travel time would provide substantial delay before the radionuclides reach the accessible environment.

The base-case probability of this scenario is estimated to be .00032 over 10,000 years, with a range of .00032 to .00003. The base-case score is judged to be 6, with a range of 2 to 9, for the first performance measure, and 6, with a range of 3 to 9, for the second performance measure. These scores are somewhat lower than those for the nominal case, reflecting the potential for a shorter radionuclide-travel time and an increased ground-water flux through the repository.

<u>Scenario 7: Movement on a small fault inside the controlled area but outside the repository</u>

The likelihood of renewed faulting in the controlled area depends on the location and extent of Quaternary faulting in the geologic setting, known subsurface faulting in the controlled area, and the earthquake-recurrence frequency. An additional component that requires evaluation for this scenario involves the observation that earthquake swarms are occurring within the basalt sequence throughout the geologic setting. The data collected in about 15 years of microearthquake monitoring indicate that the probability of earthquake swarms in the controlled area may be lower than that for other locations in the geologic setting, such as north of the site near Saddle Mountain. While this may be the case, the occurrence of earthquake swarms complicates the estimates of event probability for the controlled area. On the bases of earthquake-recurrence statistics and professional judgment, the probability of small earthquakes in the controlled area is estimated to be on the order of .001 per year, with a range of .01 to .00001 per year.

Fracture movement over a relatively small vertical extent (one to a few flow interiors) would result in relatively short pathways with a potential for reduced travel time. As discussed in the EA for the Hanford site (DOE, 1986d), the first flow top above the host rock is associated with the shorter travel times in the total travel-time distribution. Because movement on small faults does not provide extensive short-circuit pathways and because vertical fractures in flow interiors were considered in the evaluation of the nominal case, the releases would be no more severe than those expected for the nominal case. Thus, this scenario was not scored for the Hanford site.

Scenario 8: Movement on a small fault within the repository

As in scenario 7, the likelihood of renewed faulting in the controlled area depends on the location and extent of Quaternary faulting in the geologic setting, known subsurface faulting in the controlled area, the earthquake-recurrence frequency, and the occurrence of earthquake swarms near the site. On the basis of earthquake-recurrence statistics and professional judgment, the probability of movement on small faults that intersect the repository is estimated to be on the order of 10^{-5} per year, with a range of 10^{-3} to 10^{-7} per year.

In contrast to large faulting events, displacements associated with these smaller earthquakes may not be sufficient to shear waste packages. As discussed for scenario 7, movement over a relatively small vertical extent (one to a few flow interiors) would result in relatively short pathways with a potentially reduced travel time. The first flow top above the host rock is associated with the shorter travel times in the total travel-time distribution. Because movement on small faults does not provide extensive short-circuit pathways and because vertical fractures in flow interiors were considered in the nominal case, the releases for this scenario would not differ from the nominal case. Thus, scenario 8 was not scored for the Hanford site.

Scenario 9: Movement on a large fault outside the controlled area

In the geologic setting of the Hanford site there are indications, based on the evaluation of Quaternary faults, that earthquakes larger than those that have been historically observed are possible. However, on the basis of current understanding, significant movements on faults that may be associated with the Rattlesnake-Wallula Alignment (RAW) or the Gable Mountain-Umtanum trend are not expected to permanently alter the hydrologic system at the site. There is currently uncertainty about whether the Cold Creek hydrologic barrier west of the site is controlled by faulting. If this feature is controlled by faulting, the probability of significant movement would be orders of magnitude lower than that estimated for RAW because there is no geologic evidence of Quaternary movement along this feature. In addition, the Cold Creek barrier is roughly parallel to the maximum compressive-stress direction, which makes movement difficult. Under the current stress regime, any movement on this feature is likely to be strike-slip. This type of movement is not likely to result in adverse changes in the barrier. Thus, it appears that significant movement on faults outside the controlled area would not adversely affect the hydrologic system, and therefore this scenario was not scored for the Hanford site.

Scenario 10: Extrusive magmatic activity

There is no known Quaternary volcanism at the Hanford site. Volcanism in the Columbia River Basalt Group ceased approximately 6 million years ago (McKee et al., 1977). The youngest unit of the Columbia River Basalt Group at the site is the 10.5-million-year-old Elephant Mountain Member of the Saddle Mountain Basalt (Myers, 1981). Quaternary volcanism has occurred in the western Columbia Plateau where the Columbia River Basalt Group onlaps the Cascade Range. However, this Quaternary basaltic volcanism (the Simcoe volcanic series) appears to be more closely allied to the Cascade volcanism because of its calc-alkaline composition compared with the tholeitic basalt of the Columbia River Basalt Group. Estimates of volcanism indicate that the probability of volcanism at the Hanford site is less than 10^{-8} per year (A. D. Little, Inc., 1980). In view of this estimate and the above information, the probability of a disruption in the vicinity of the repository in 10,000 years is estimated to be less than 1 chance in 10,000. Therefore, this scenario is not credible at the Hanford site.

Scenario 11: Intrusive magmatic activity

This scenario is not credible at the Hanford site for the reasons given for Scenario 10.

Scenario 12: Large-scale exploratory drilling

The EPA has concluded that the likelihood of inadvertent and intermittent drilling need not be taken to be greater than 30 boreholes per square kilometer of repository area per 10,000 years for geologic repositories in proximity to sedimentary rock formations and no more than 3 boreholes per square kilometer per 10,000 years in other geologic formations (40 CFR Part 191, Appendix B). This conclusion is based on historical information for the Hanford site, as well as on projections of hydrocarbon exploration in the immediate area. In fact, the probability of drilling more than about 3 boreholes per square kilometer is estimated to be much less than 10^{-8} per year (Arthur D. Little, Inc., 1980; Lee et al., 1978). It might be argued that drilling for natural gas at the Hanford site might involve reaching the sediments underlying the basalt flows and thus fall within the EPA category of geologic repositories in proximity to sedimentary rock formations. However, it is clear from the historical record and from the projections made by the EPA that large-scale drilling at the Hanford site is very unlikely. Because of negligible probability for large-scale drilling, the Hanford site was not scored for this scenario.

Scenario 13: Small-scale exploratory drilling

The EA (DOE, 1986d) reports about 25 water wells drilled during the past 40 years to depths greater than 300 m in the 4900 km^2 area of the Pasco Basin. This frequency extrapolated to 10,000 years is about 1.3 boreholes per km^2. The projections by the EPA have concluded that the probability of drilling three boreholes per km^2 in 10,000 years is less than .0001, not taking into account the passive institutional controls at the site (A. D. Little, Inc., 1980). Therefore, the probability of any drilling that could affect repository performance at the Hanford site is expected to be very low.

The repository area is expected to be about 8 km^2, which requires that 24 boreholes must be considered in this evaluation. Of these, no more than two would result in preferential pathways for radionuclide transport. Direct releases would not be significant. By assuming a vertical gradient of 0.001, a conductivity for the borehole of 10^4 m/yr, and a borehole area of 0.04 m^2, a flow rate of 0.4 m^3/yr is obtained, or 4000 m^3 of water per 1000 MTHM in 10,000 years, for the two boreholes. This flow rate would lead to an F value of 1.6×10^{-4} for the first 10,000 years and 1.6×10^{-4} in the period between 10,000 and 100,000 years. These factors are less than those estimated for transport through the rock, reflecting the limited volume of water that would actually flow through the boreholes. In this case, the score should not be significantly different from that for the nominal case. Thus, the impacts of drilling at the Hanford site were judged to be negligible, and the site was not scored against this scenario.

Scenario 14: Incomplete sealing of the shafts and the repository

Failure of the shaft seals at the Hanford site is more probable than at the salt sites. There is little or no experience with sealing of the type contemplated for the basalt flows. For example, there is little experience with grouting to thoroughly seal off the disturbed rock adjacent to the shafts. Therefore, the base-case probability that this scenario will result in impacts on the repository performance over the first 10,000 years is judged to be .01, with a range of .001 to .1.

Although failure of the shaft and repository seals would allow saturation of the repository at the Hanford site, rapid resaturation because of seepage through the host rock is already expected at the site. The flow through the failed seal system is estimated to be about 0.3 m^3/yr, assuming an effective cross-sectional area of 30 m^2, a conductivity of 10 m/yr, and a vertical gradient of 0.001. This flow rate amounts to about 40 m^3 per 1000 MTHM in 10,000 years, which is well within the range considered for the nominal case. Therefore, the F value is considered to be similar to that for the nominal case.

The ground-water-travel time might be different than that for the nominal case, however. The shaft could provide a preferential pathway to an overlying transmissive interbed such as the Vantage in which the travel time is considerably shorter than in the basalt flow tops in the Grand Ronde Formation. In this unit, a median travel time of less than 1000 years cannot be precluded. For example, for a distance to the Vantage interbed of about

130 m, an effective porosity of 0.01, a hydraulic gradient of 0.001, and an effective conductivity of 10 m/yr for the seal system, the time of ground-water travel to the Vantage interbed would be only about 130 years.

Because the radionuclide-travel time can be reduced from the nominal case, the base-case score for the Hanford site is judged to be 7, with a low-to-high range of 3 to 10, for both performance measures.

D.6 YUCCA MOUNTAIN SITE

Scenario 1: Nominal case (expected conditions)

For the purposes of this analysis, it is assumed that the repository at Yucca Mountain would be constructed more than 230 m below the surface in the lower portion of the densely welded Topopah Spring Member of the Paintbrush Tuff. It is assumed that the mined area would occupy less than 25 percent of the underground repository area and that the 70,000 MTHM of spent fuel would be distributed in about 20,000 waste packages (3.4 MTHM per package) over about 6 km^2. The host rock is in the unsaturated zone, and the repository is at a mean distance of more than 200 m above the water table.

It is difficult to determine the flux through the host rock. Estimates range from 10^{-10} to 5×10^{-4} m^3/m^2-yr averaged over the repository area. Using this range and an effective cross-sectional area of 30 m^2 per waste package, the volume of water that could be available for waste-package corrosion and waste dissolution ranges from 0.009 m^3 to 44,000 m^3 per 1000 MTHM during the first 10,000 years. The volume available in the next 90,000 years would be about 9 times greater. A pluvial cycle commencing 15,000 years after repository closure might increase the ground-water infiltration rate, perhaps by 100 percent over this amount, based on a 100-percent increase in precipitation during the pluvial period. This factor was taken into account in arriving at the estimates of the volume of water available for the dissolution of the waste.

This water may be available to corrode waste packages and dissolve waste. However, it is not clear that this flux will actually flow into the repository void spaces in the unsaturated zone, since the suction pressure of the rock is so high. Furthermore, it is not clear that water will not be driven away from the repository because of the potential for rock temperatures to exceed the boiling point of water in the repository. Nevertheless it seems prudent to assume that this water might be available. Estimates of waste-package lifetime using these volumes of water result in lifetimes of 3000 to 30,000 years.

The conceptual model for ground-water movement postulates that the flux of water is vertically downward in the unsaturated zone, while the movement in the underlying unconfined aquifer in the Calico Hills and Bullfrog Members is essentially lateral.

It is assumed that the ground-water movement in the unsaturated zone is dominated by movement through the rock matrix rather than through the fractures. The rock is highly fractured but the matrix potential is very high. Fracture flow is currently believed to become predominant when the flux is on the order of 5×10^{-3} m^3/m^2-yr or more. For this flux, the median time of ground-water travel to the water table is estimated to be about 42,000 years. For a flux closer to the expected value, the median travel time could be as long as 200,000 years. These estimates are based on pre-waste-emplacement conditions. Post-waste-emplacement conditions may result in even longer travel times. The movement of ground water in the saturated zone is essentially fracture flow and is more rapid; lateral movement contributes only a few hundred to a thousand years to the travel time. The travel time could be decreased somewhat during a pluvial cycle. However, this effect is not expected to be large unless locally saturated conditions occur. Otherwise, the ranges of flux that might result from changes during a period of increased rainfall are not expected to give a range of travel times different from that already considered. Therefore, the range in the median ground-water-travel time is considered to be 42,000 to 200,000 years.

Sorption is important for many of the radionuclides. However, for key radionuclides, such as technetium, it is possible that sorption may be very low. On the other hand, since matrix diffusion is estimated to provide a retardation factor of 100 to 1000, even the weakly sorbed radionuclides are likely to be strongly retarded.

The radionuclide-concentration limits considered in the EA (DOE, 1986e) are summarized in Table D-1. Values for particular radionuclides could vary by several orders of magnitude above or below the values given in the EA. However, the controlling factor in the estimates in Table D-1 is the solubility of the UO_2 in the ground water. The solubility of 50 ppm that is used is considered to be very conservative; therefore, it is assumed that the concentration limit would not be greater than the values based on these solubilities. The sum of the ratios of the derived isotopic solubility limits and the EPA release limits is also given in Table D-1. These values can be used in conjunction with the available volume of water to estimate dissolution rates.

These site characteristics are summarized in Tables D-2 and D-3, along with the associated performance factors. The results are strongly dependent on the assumed ground-water flux. If the flux were higher, travel times could become very short, waste-dissolution rates could be higher, and waste-package corrosion could be increased. These site characteristics and performance factors indicate that releases to the accessible environment are expected to be insignificant. However, because so much of the performance depends upon the flux and because there is current uncertainty in the magnitude of this parameter at the site, there is uncertainty in the score for the Yucca Mountain site for the nominal case. The base-case score for the first performance measure is judged to be 10, with a low score of 5. For the second performance measure, the base-case score is judged to be 9, with a low-to-high range of 5 to 10.

Scenario 2: Unexpected features

Figure D-5 indicates the range of unexpected features that could occur at the Yucca Mountain site. The extreme conditions that could result from these features are those that were not considered in the range of expected

UNEXPECTED FEATURES ↓	ROCK CHARACTERISTICS		GEOHYDROLOGY				GEOCHEMISTRY			
	SIGNIFICANT CHANGE IN HEAT CONDUCTION	SIGNIFICANT CHANGE IN MECHANICAL STRENGTH & DEFORMATION	CHANGE IN GROUND-WATER FLOW MECHANISM	NEW GROUND-WATER FLOW PATHS	SIGNIFICANT CHANGE IN HYDROLOGIC PROPERTIES	SIGNIFICANT CHANGE IN HYDRAULIC GRADIENT	SIGNIFICANT CHANGE IN SOLUBILITY, LEACH RATE, CORROSION, ETC., DUE TO TEMPERATURE INCREASE	CHANGE IN GROUND-WATER CHEMISTRY FROM NEW WATER SOURCE	LOW-GRADE METAMORPHISM OF ROCK, BACKFILL	CHANGE IN STATE FROM EQUILIBRIUM TO KINETIC
REPOSITORY-INDUCED SUBSIDENCE/UPLIFT		●	●	●	●	●				
UNDETECTED FAULT ZONES (cm < w < 1 m)		●	●	●	●	●				
UNDETECTED SIGNIFICANT LATERAL VARIATIONS	●	●			●		●		●	
UNDETECTED DIKES, SILLS										
UNDETECTED VERTICAL HETEROGENEITY (PERCHING)			●	●	●	●				
OTHER	●	●	●	●	●	●	●		●	

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Figure D-5. Unexpected features at the Yucca Mountain site.

conditions in the nominal case. These conditions include, for example, the possibility (labeled "other" in Figure D-5) that fracture flow dominates matrix flow or that ground-water movement is dominated by vapor-phase flow. The probability that extreme conditions outside the expected range could occur at the site and affect performance is small. The base-case probability is judged to be .019, with a range from 0 to .2.

The impacts of extreme conditions that result from unexpected features could lead to releases that could be as much as 10 times greater than those for the nominal case because, for example, of shorter travel times. Uncertainties in the score are large. The base-case score is judged to be 8, with a low-to-high range of 2 to 10, for both performance measures.

Scenario 3: Repository-induced dissolution of the host rock

Potential disruption of expected repository performance because of dissolution applies only to relatively soluble media. Hence, this scenario is not considered to be credible at the Yucca Mountain site.

Scenario 4: Advance of a dissolution front

Potential disruption of expected repository performance because of dissolution applies only to relatively soluble media. Hence, this scenario is not considered to be credible at the Yucca Mountain site.

Scenario 5: Movement on a large fault inside the controlled area but outside the repository

At the Yucca Mountain site there are a number of Quaternary faults within 10 km of the site, and some of them pass through the proposed controlled area. Because full evaluation of each fault (age and slip rates of movement) is not yet completed, it is not possible to determine specific probabilities for movement on each separate fault. Recurrence statistics based on data reported by Greensfelder et al. (1980), Algermissen et al. (1982), and Rogers et al. (1977), adjusted to the size of the controlled area, suggest that the probabilities of earthquake magnitudes greater than about 6 are on the order of 5×10^{-5} per year, with a range of 2×10^{-4} to 10^{-6}.

As described under the nominal case for Yucca Mountain, the current understanding is that flow in the unsaturated zone moves predominantly downward through the rock matrix until it reaches the saturated zone, where flow is predominantly lateral through fractures to the accessible environment. Fault movement within the controlled area is unlikely to change the characteristics of this flow pattern. In particular, ground-water travel time in the saturated zone is assumed to be relatively rapid and any renewed movement on a large fault is not likely to significantly decrease travel times in the saturated zone. Since flow is assumed to be vertical in the unsaturated zone, between the repository horizon and the water table, fault movement outside this zone of vertical flow would not alter the expected flow. Thus, while there is a relatively high probability of earthquake occurrence, there is no credible mechanisms for an event within the controlled area to alter expected releases. Therefore, this scenario would not provide impacts more severe than those for the nominal case and thus was not scored for the Yucca Mountain site.

Scenario 6: Movement on a large fault within the repository

Because of the size of the repository as compared with the total controlled area, the probability of renewed movement on a large through-going fault is at least 10 times lower than that estimated for scenario 5. For the Yucca Mountain site, this results in a probability that is on the order of 10^{-6} per year, with a range of 10^{-5} to 10^{-7}.

As discussed under the nominal case for Yucca Mountain site, numerous fractures exist in the stratigraphic units both above and below the repository. However, the ground-water movement is predominantly through the matrix rather than through the fractures. Renewed fault movement is not likely to alter this condition, primarily because faulting would not be expected to bring additional volumes of water into the unsaturated zone. If a zone of perched water were intersected by renewed faulting, flow through the fault would be transferred into the matrix by the strong negative pressure within the pores of the unsaturated matrix over relatively short vertical distances.

The early loss of waste packages because of shearing may not be significant because the radionuclide-travel time provides substantial delay before the radionuclides reach the accessible environment. Thus, while there is a relatively high probability of fault movement, there are no credible mechanisms for the occurrence of a faulting event that could intersect the repository and alter expected releases. Thus, this scenario was not scored for the Yucca Mountain site.

Scenario 7: Movement on a small fault inside the controlled area but outside the repository

From the location and number of faults in the controlled area and earthquake-recurrence rates published in the literature, it can be concluded that the Yucca Mountain site has a relatively high probability of earthquake occurrence. However, because flow is expected to generally occur in the rock matrix, rather than in the fractures, movement on small faults within the controlled area, including those that intersect the repository, is not expected to affect repository performance. Thus, this scenario was not scored for the Yucca Mountain site.

Scenario 8: Movement on a small fault within the repository

As discussed briefly in scenario 7, it can be concluded that the Yucca Mountain site has a relatively high probability of earthquake occurrence. However, because flow is expected to generally occur in the rock matrix, rather than in the fractures, large events within the controlled area, including those that intersect the repository, are not expected to affect radionuclide releases. Small fracture movement would not alter the expected flow in either the unsaturated zone or the saturated zone. Any damage to waste packages is not likely to lead to significant consequences because the radionuclide-travel time is so much greater than the waste-package lifetime under the expected conditions. Thus, this scenario was not scored for the Yucca Mountain site.

Scenario 9: Movement on a large fault outside the controlled area

Of the five nominated sites, the likelihood of significant movement on a fault outside the controlled area is greatest at the Yucca Mountain site. Because most of the radionuclide-travel time occurs as transport in the unsaturated zone, and because flux in the unsaturated zone is independent of faulting, the only identified mechanism that could alter releases would be an increased elevation of the water table. However, many large displacements would be required to significantly modify the vertical position of the water table. Small changes in the position of the water table are not significant in terms of changing the radionuclide-travel time to the accessible environment. Credible movements along known faults within about 10 km of the Yucca Mountain site would not be expected to result in significant changes to the water table. Because any credible events would have no consequences, this scenario was not scored for the Yucca Mountain site.

Scenario 10: Extrusive magmatic activity

There is no evidence of Quaternary magmatic activity at the site. However, Quaternary volcanism has occurred within the geologic setting. Available information indicates that silicic volcanism ceased at least 8 million years ago in the southern Great Basin. Basaltic volcanic activity has continued during the last 6 to 8 million years, but in episodes that are separated by hundreds of thousands of years (Crowe et al., 1982). The most recent episode of basaltic activity near Yucca Mountain occurred approximately 270,000 years ago.

Two methods have been used to determine the rate of volcanic activity at the site. The first is to determine the annual rate of magmatic production in the vicinity of the site. A significant finding from these studies is that there is an apparent decline in the rate of magma production (surface eruptive products calculated as magmatic volume equivalents) for this area during the past 4 million years (Vaniman and Crowe, 1981). This is consistent with other studies that have identified a decrease in the rate of volcanic activity responsible for basaltic volcanism (Crowe et al., 1982). The second method to determine the likelihood of magmatic activity is by evaluation of the density of volcanic cones in the area. Correcting for the likelihood of an occurrence at the Yucca Mountain site, the annual probability of volcanic disruption within 10 m^2 of an assumed repository is calculated to be 2.9 x 10^{-8} (Crowe and Carr, 1980). A more recent report the annual probability of volcanic disruption at a waste repository at Yucca Mountain to be between 4.7 x 10^{-8} to 3.3 x 10^{-10} (Crowe et al., 1982). These estimates indicate that the probability of repository disruption because of basaltic volcanism would be very low.

Nevertheless, it is possible for the probability of an event in the next 10,000 years to be somewhat greater than 1 chance in 10,000. The probability of this scenario during the next 500 years is judged to be 5 x 10^{-8}, with a range of 5 x 10^{-6} to 10^{-10} over 500 years.

In order to establish a basis on which to score the site, it is assumed that the dike would be about 4 m wide and extend over a length of about 4 km. Estimates by Link et al. (1982), taking into account the random orientation of the dike with respect to the repository and the density of waste packages in the repository, indicate that about seven waste packages could be contacted by the dike. This estimate is considered to be conservatively high because planes of structural weakness along which a dike would form have a definite orientation at the site. The inventory of waste in this number of packages in the first 500 years would correspond to between 5 and 50 times the EPA release limits if all this waste was released to the accessible environment (DOE, 1980). It is possible that very little of the waste would actually be entrained into the magma. Furthermore, the waste reaching the surface would be fixed into basalt and not necessarily be available for release to the accessible environment. Erosion of the cooled lava could result in a release of radionuclides. On this basis, the base-case score is judged to be 2, with a low-to-high range of zero to 7, for the first performance measure. During the time period 10,000 to 100,000 years, radioactive decay will reduce the radioactivity in the waste entrained in the magma. In addition, if the event occurs early, it is likely that most of the release would occur in the first 10,000 years and only a small fraction after this time. The base-case score for the second performance measure is judged to be 7, with a low-to-high range of 3 to 9.

For evaluation of an event that occurs after 500 years, the consequence decreases because the inventory decreases. For example, the inventory for seven packages ranges between two and five times the EPA limits in 10,000 years. The base-case score for the first performance measure is judged to be 3, with a low-to-high range of 0 to 7. For the second performance measure, the base-case score is judged to be 7, with a low-to-high range of 2 to 10.

The base-case probability of a late event occurring between 500 and 10,000 years is estimated to be 10^{-6}, with a range of 10^{-4} to 10^{-10}.

Scenario 11: Intrusive magmatic activity

The geologic history of Yucca Mountain suggests that basaltic volcanism is barely credible at the site. Furthermore, this evidence suggests that plutonic intrusion has a much lower probability at the site. Therefore, intrusive magmatic activity is not considered to be credible at this site. Further, the consequences of an intrusive magmatic event are probably bounded by the extrusive-event scenario for the Yucca Mountain site. Thus, the Yucca Mountain site was not scored against this scenario.

Scenario 12: Large-scale exploratory drilling

The EPA has concluded that the likelihood of inadvertent and intermittent drilling need not be taken to be greater than 30 boreholes per square kilometer of repository area per 10,000 years for geologic repositories in proximity to sedimentary rock formations nor more than 3 boreholes per square kilometer per 10,000 years in other geologic formations (40 CFR Part 191, Appendix B). The probability of drilling 30 boreholes per square kilometer in 10,000 years is estimated to be slightly less than 1 chance in 10,000 in sedimentary basins and much less than this for other types of rock formations, such as at the Yucca Mountain site (Arthur D. Little, Inc., 1980). Because of the negligible probability for large-scale drilling at the Yucca Mountain site, this scenario was not scored.

Scenario 13: Small-scale exploratory drilling

The EPA has concluded that the likelihood of indirect and intermittent drilling in geologic formations like those at Yucca Mountain need not be taken to be greater than 3 boreholes per square kilometer in 10,000 years (40 CFR Part 191, Appendix B). However, even if exploratory drilling were to take place at the Yucca Mountain site, the consequences would be insignificant. Because of the high suction pressure of the rock in the Topopah Spring Member, influx through the borehole would be likely to be taken up by the matrix. Thus, no additional flux would occur beyond that considered in the nominal case. No significant consequences are expected at the Yucca Mountain site because of drilling, and therefore the site was not scored against this scenario.

Scenario 14: Incomplete sealing of shafts and the repository

Failure of the shaft and repository seals is not expected to provide significant impacts on the site performance factors at the Yucca Mountain site. No additional flux would be introduced into the repository, and the radionuclide-travel times would not be affected as long as the average flux is low enough to be dominated by matrix flow. Therefore, this site was not scored against this scenario.

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Appendix E

INFLUENCE DIAGRAMS AND PERFORMANCE MEASURES FOR PRECLOSURE OBJECTIVES

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Appendix E

INFLUENCE DIAGRAMS AND PERFORMANCE MEASURES FOR PRECLOSURE OBJECTIVES

Chapter 4 briefly described the performance measures associated with the preclosure siting objectives. It was noted that there are basically two kinds of performance-measure scales: natural and constructed. Natural scales enjoy common usage, such as dollars. Constructed scales must be developed for the problem at hand--for example, socioeconomic impacts. The purpose of this appendix is to describe the basis for the choice of the measures presented previously, in particular the choice of the technical descriptors that influence the extent to which a site is likely to achieve an objective.

The process of selecting descriptors was systematic and comprehensive, and was aided by the construction of influence diagrams for each measure. Influence diagrams are a tool for communicating and clarifying the technical considerations that link performance measures with objectives. Each diagram should reflect a natural logical flow that is intuitive. They are not unique, but should seem reasonable to the informed reader. The lower-level factors whose arrows lead into a given higher-level factor should represent distinct characteristics that, if known, would largely eliminate the uncertainty in the higher-level factor. The lowest-level factors represented in the influence diagram (those factors that have no arrows leading into them) should represent fundamental characteristics for which further disaggregation provides no significant additional insight.

Influence diagrams were generated through an iterative process involving both technical specialists and decision analysts. For each siting objective, a workshop was conducted to produce a preliminary diagram. The first step in the workshop was to select a direct measure that indicates the degree to which the objective is met. For example, the total number of fatalities might be chosen as a direct measure for the objective "minimize nonradiological health effects to facility workers." The most significant influencing factors were then identified by asking, "What key pieces of information would resolve uncertainty over that value of this measure?" Other formulations of this question were also used to help identify influencing factors.

As key factors were identified, they were added to the diagram. The process was then continued by identifying additional factors influencing the already identified factors. The process of identifying additional factors for the diagram was continued until it reached a level of fundamental characteristics that do not need to be broken down. To avoid unnecessary complexity, identified factors were tested and removed if they failed to satisfy the following requirements: (1) each factor must be significant in the sense that its influence on the factors to which its arrow leads are significant relative to the other factors with arrows that lead to the same factors and (2) the factors must differ for at least two of the nominated sites. (Sometimes, a factor that does not differ among sites was left in the diagram because its inclusion is necessary to clarify the logic underlying the diagram.)

The final step in the development of the preliminary diagram was to identify the most significant or important of its influencing factors. Double ellipses were drawn around these factors. The lowest-level factors with double ellipses then represent the key site characteristics tentatively identified as the basis for developing the performance measures.

Once preliminary diagrams were developed, members of the workshop reviewed the preliminary diagrams with colleagues and others to identify refinements and revisions. These revisions were reviewed by decision analysts to ensure that consistency with the logic of influence diagrams was maintained. Once consensus had been obtained for the structure of an influence diagram, its most significant factors (double-ellipse factors) were identified as the basis for the performance measure, which was then used to score the sites.

For some objectives, detailed analytical models that directly calculate the impacts were available. For example, detailed models and data were available to calculate impacts for all of the transportation objectives that are related to health and safety. In these instances, the construction of influence diagrams merely aids the reader in identifying the major inputs to the models. For several of the other performance objectives, models were used to calculate major inputs to the evaluations of the sites. For example, total labor requirements, a key input to the calculation of nonradiological fatalities in repository workers, were computed by the same model that calculates total facility costs. For the objectives that require constructed scales, analytical models in the sense described above do not exist, and thus impacts must be evaluated indirectly (e.g., socioeconomic impacts).

The sections that follow present the influence diagram for each preclosure objective together with some explanatory text.

E.1 OBJECTIVES RELATED TO HEALTH AND SAFETY

These are eight objectives that are related to health and safety, four associated with the repository facility itself and four with waste transportation. Two radiological and two nonradiological objectives are included in each group. The objectives associated with the facility are described first in this section, followed by the objectives associated with transportation.

E.1.1 PERFORMANCE OBJECTIVE 1

Performance Objective and Performance Measures

Performance objective 1 is to minimize the preclosure radiological health effects that are experienced by facility workers and are attributable to the facility. The performance measure is the number of radiological health effects in facility workers.

Influence diagram

The diagram is shown in Figure E-1 and is described below. The numbers in parentheses identify the various influence factors. The number of preclosure radiological health effects (1) that are experienced by facility workers and are attributable to the facility depends on the dose-response relationship (28) and radiological exposures from routine operations (including construction) or accidental occurrences (2,3, and 4). Routine operations can be conducted on the surface or underground. While included for completeness, accidents that occur at the site are expected to have comparable consequences to the exposed workers at each site and are therefore nondiscriminating considerations in the influence diagram.

Routine operations at the surface. There are three kinds of routine operations at the surface that can result in radiation exposure: waste receiving, waste handling hot cells, and hot cell to hoist operations. Waste-receiving operations include the unloading of shipping casks from trucks or rail cars, the unloading of the waste, storing the waste, and moving the waste to the hot cell. Radiation exposures will occur from direct exposure to the waste casks as well as from such activities as the management of the low-level liquid wastes that are generated during the washdown and decontamination of casks. Hot-cell operations will result in exposures from activities related to the preparation of the waste for disposal (e.g., removing the spent-fuel rods from the hardware that holds them together, loading into disposal containers, decontamination, and disposal of any radioactive wastes generated in the process). Hot cell to hoist operations will involve the storage and handling of the waste containers on the surface. For clarity, this detail is not shown in the influence diagram.

Exposures due to normal surface operations (2) depend on the radiological characteristics of the casks and waste packages (7), the number of workers exposed per operation (8), the duration of worker exposure per operation (10), and the number of operations (9).

The radiological characteristics of the casks or the waste packages (7) depend on their designs (14, 16): the amount of waste per package, the thickness of the container walls, the type of container material, the type of waste, etc.

The number of waste-handling and waste-processing operations is proportional to the number of casks (15) and waste packages (17) that are handled. The numbers of casks and waste packages that are required depend on their designs (14, 16).

The waste-package design depends on the characteristics of the host rock (27), the most important characteristic being thermal conductivity. The ability of the host rock to dissipate heat dictates the size of the waste package (i.e., the amount of waste per package) and the spacing between packages. Rock with a low thermal conductivity would require smaller packages (less waste per package but more packages) and/or greater spacing between packages.

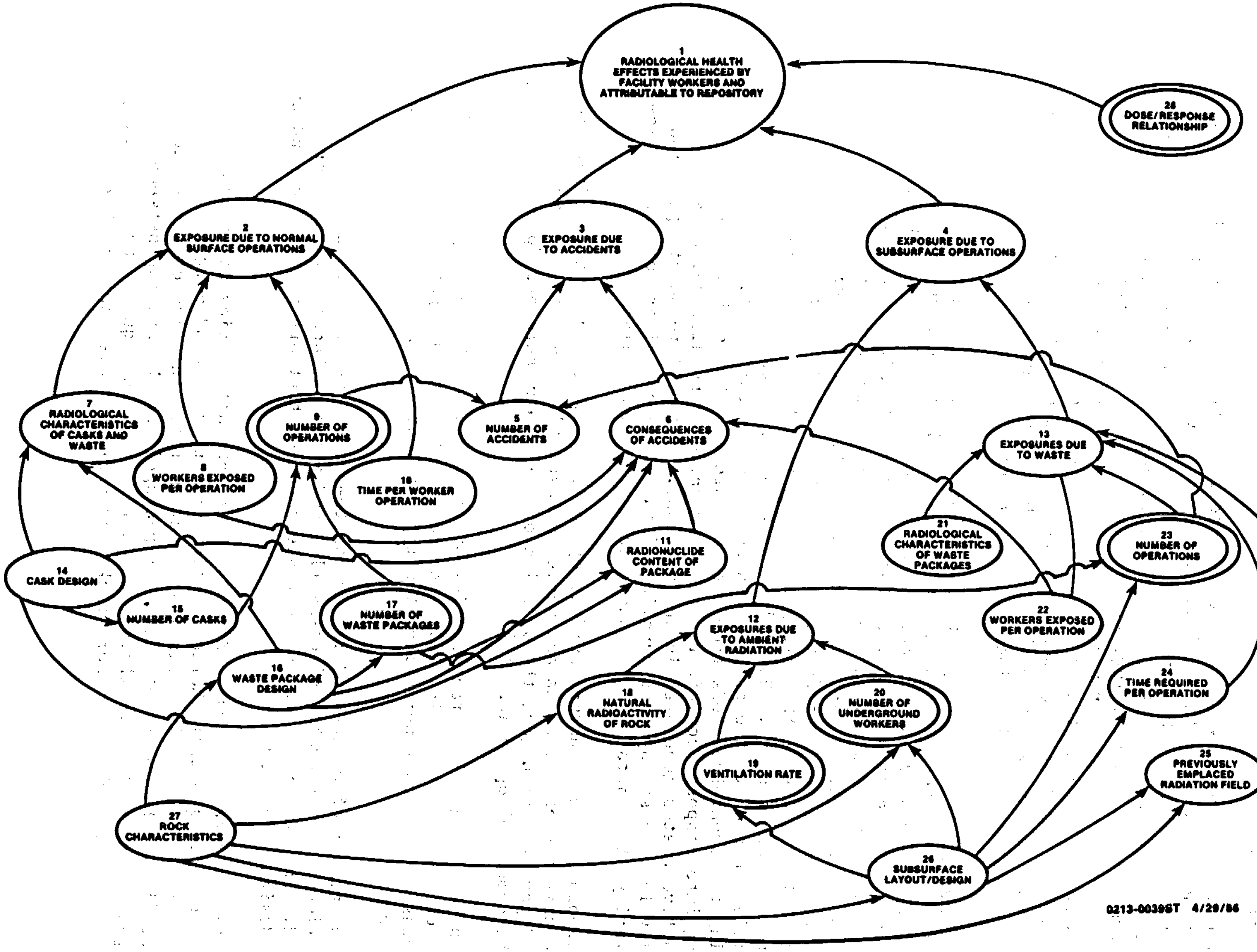

Figure E-1. Factors that influence the radiological health effects incurred by repository workers.

Routine operations underground. The underground operations that can result in radiation exposures (4) are (1) shaft (or ramp) operations, which involve the transfer of the waste to the underground repository; (2) underground transport operations, which involve moving the waste containers from the hoist to the emplacement room; and (3) emplacement operations, which involve emplacing the waste containers into the emplacement holes. For clarity, this detail is not shown in the influence diagram. For the workers involved in these operations, exposures (12) will result from the natural radioactivity of the host rock (18) -- that is, exposure to released radon -- and from the radiation from the waste packages (13) -- that is, direct exposure to a waste package and the radiation field created by other waste packages already emplaced.

Exposures due to ambient radiation (12) depend on the natural radioactivity of the rock (18), the ventilation rate (19), and the number of underground workers (20). Rock with a very low natural radioactivity will not yield any significant radiation exposure regardless of the ventilation rate. In rock with moderate radioactivity, the radiation exposure of workers can be reduced by providing adequate ventilation so that radon concentrations do not build up in the repository. Most workers exposed to the ambient underground conditions would stay underground for the entire work shift, and therefore the duration of exposure is not a discriminator.

The ventilation rate (19) is directly related to the size, layout, and design (e.g., the number and location of ventilation shafts, size of ventilation equipment). Radon control may be a secondary purpose of ventilation, the primary purpose being temperature or dust control.

The exposures of workers to radiation from the waste itself depend on several factors, including the radiological characteristics of the waste packages (21) the number of operations (23) the number of workers exposed per operation (22) and the duration of exposure for each worker for each operation. In addition, underground workers, particularly those working in the waste-emplacement rooms, are exposed to the radiation field created by previously emplaced waste packages (25).

The number of underground workers depends on the layout and design of the underground repository (26) and the characteristics of the host rock (27). For example, the number of workers is affected by the quantity of rock to be mined and the mining techniques that must be used.

The time required for an underground operation depends mainly on the underground layout and design (26). For example, the distance between the hoist shaft and the emplacement rooms could affect the exposure time for workers. Close spacing between waste packages could increase the time required to emplace a package to avoid disturbing previously placed packages. The use of horizontal emplacement holes could require emplacement times that differ from those for vertical emplacement.

The exposures of workers from previously emplaced waste packages depend on the underground layout and design (26), in particular the spacing between waste-emplacement holes and the radiological characteristics of the emplacement-hole and the characteristics of the rock (27) -- that is, the shielding properties of the rock.

The layout and design of the underground repository depend on the characteristics of the rock (27), such as thermal conductivity, internal stress, tendency to close in salt formations, and requirements for roof support. Thermal conductivity is the rock characteristic that has the greatest effect on the layout and design (i.e., waste-package spacing).

Accidents. Radiological health effects due to accidents depend on the number of accidents (5) and their consequences (6).

The number of accidents (5) involving waste package is a function of (9) (23) the number of surface and subsurface handling operations. Accidents could occur during receipts (e.g., dropping a cask), during host-cell operations (e.g., fire, explosion, or dropping a fuel assembly) or during waste transport or emplacement (e.g., a hoist drop).

The radiological consequences of waste package handling accidents depend on the radionuclide content of the cask or waste package. Radionuclide content depends on the design of the cask or waste package (14) (16). The design of a cask or waste package influences the radionuclide release that would result from a handling accident. The number of exposures also depends on the number of workers (8) present when the accident occurs.

E.1.2 PERFORMANCE OBJECTIVE 2

Performance objective and performance measure

This performance objective is to minimize the preclosure radiological health effects experienced by the public and attributable to the facility. The performance measure is the number of radiological health effects.

Influence diagram

The diagram is shown in Figure E-2 and is described below.

The preclosure radiological health effects experienced by the public and attributable to the facility (1) can occur through three mechanisms: inhalation (2), submission (3), and ingestion (4). Inhalation may involve the radon gas released from the repository rock or in the form of radioactive particulates released by a waste-handling accident. Exposure through submersion would occur if airborne or water borne releases are deposited in a water body outside the controlled area and people swim or bathe in the water. The ingestion mechanism involves both the drinking of water contaminated by a release and the eating of crops that have taken up radionuclides.

Radionuclide releases can result from routine operations (20) and accidental occurrences (23). The releases in routine operations consist of the radon emitted from the rock and airborne releases (22) of other radioactive gases and particulates. Accidental releases result from a loss of waste containment in such occurrences as a hoist-drop accident or an accident in waste handling or preparation.

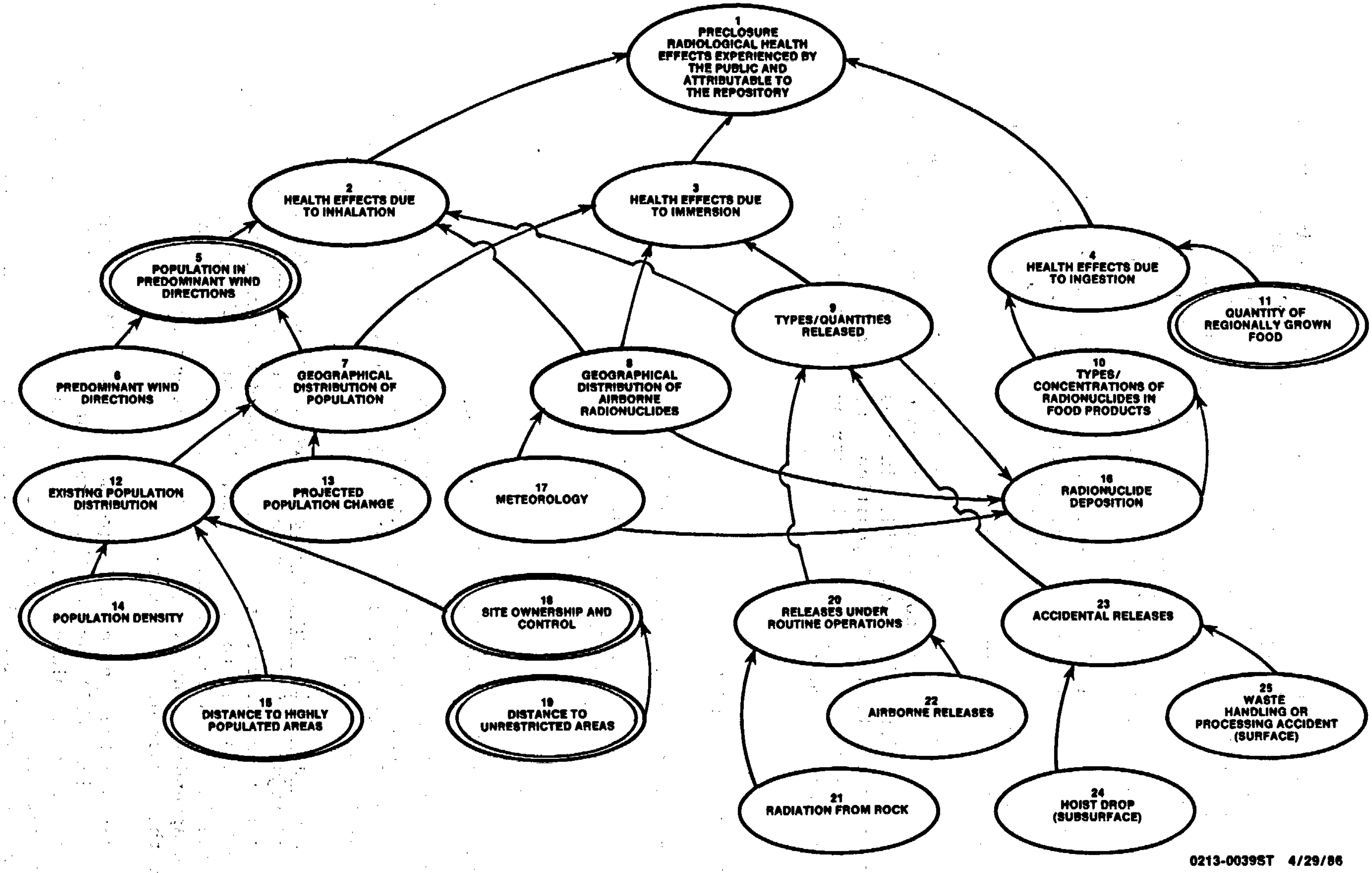

Figure E-2. Factors that influence the radiological health effects incurred by the public from the repository.

The number of health effects due to inhalation is determined by the types and the quantities of released radionuclides released (9); the geographical distribution of airborne radionuclides (8); and the population in the predominant wind direction, which is determined by the population distribution (7) and the predominant wind direction (6). The population distribution is affected by population changes (13) and the existing population (12), which depends on the population density (14), distances to populated areas (15), and site ownership and control (18) (Federal, State, or private).

The number of health effects due to submersion is influenced by the types and the quantities of the released radionuclides (9), the geographical distribution of airborne radionuclides (8), and the population distribution (7). The distribution of airborne radionuclides determined by meteorology (17), in particular atmospheric dispersion.

The number of health effects due to ingestion depends on how much of the food consumed by the affected population is grown in the region (11) and the types and concentrations of radionuclides in food products (10), which depends on radionuclide deposition (16). Deposition depends on the types and the quantities of releases, the geographical distribution of airborne radionuclides, and meteorology.

E.1.3 PERFORMANCE OBJECTIVE 3

Performance objective and performance measure

This performance objective is to minimize nonradiological health effects in facility workers. The performance measure is nonradiological deaths of facility workers.

Influence diagram

The diagram is shown as Figure E-3 and is described below.

Nonradiological health effects in facility workers can be divided into three categories: the number of underground fatalities and injuries (2), the number of surface fatalities and injuries (3), and the number of chronic fatalities and illnesses (4).

Underground fatalities and injuries. The number of underground fatalities and injuries (2) is determined by the rate of underground accidents (6) and the number and distribution of underground workers (5), such as the number of workers assigned to each job and the size of the groups in which they work; the latter is determined by the subsurface conditions (17). As is explained in Appendix F, however, a constant accident rate is assumed in calculating the number of fatalities.

The number and the type of underground accidents (6) is influenced by subsurface conditions (17) through the number of rock falls (12); the number of rock bursts (13); the mining techniques and equipment required (14), since different techniques lead to different accident types and frequencies; the gases present (15), which depends on rock characteristics and mining techniques; equipment failure due to corrosion (11), which depends on

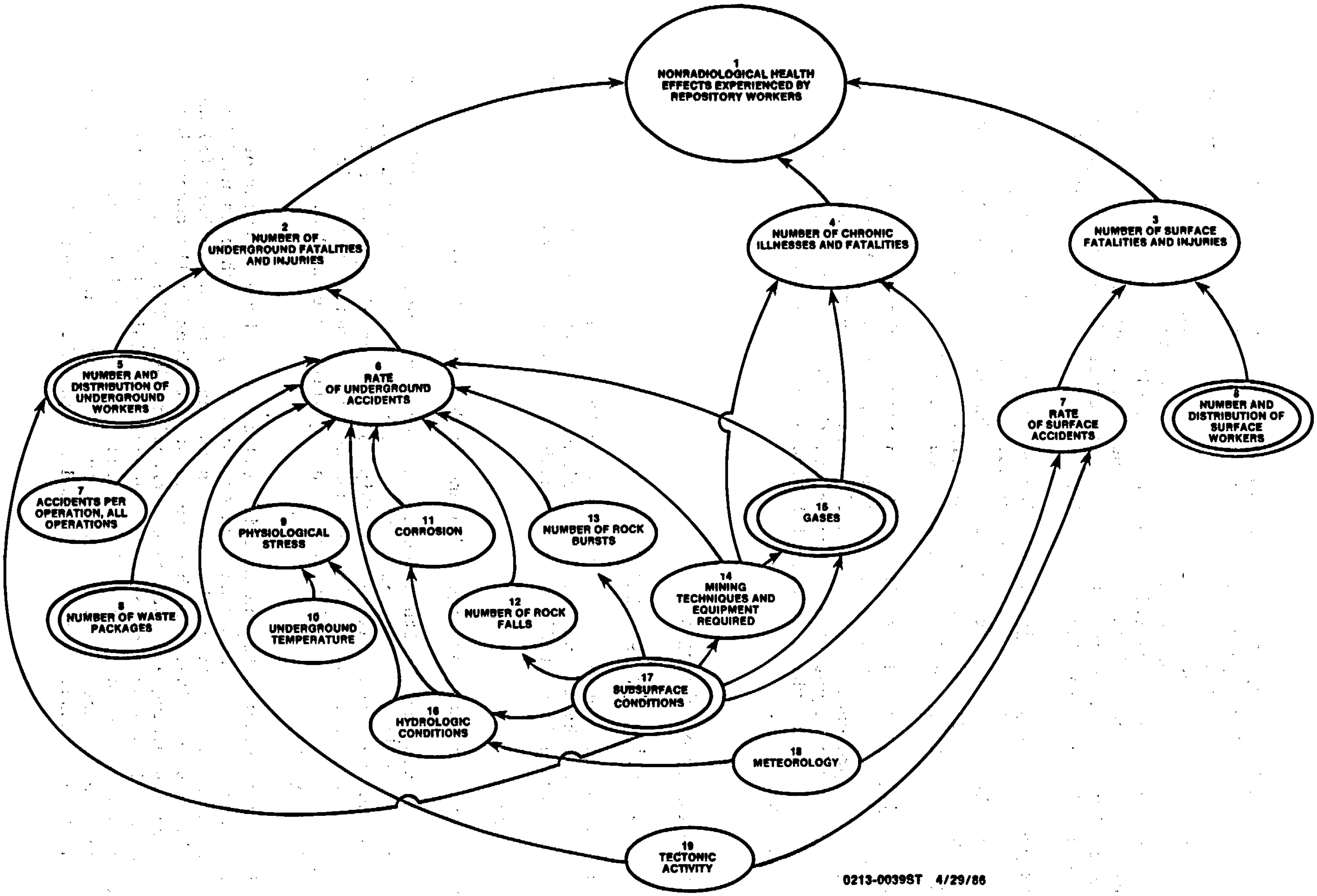

Figure E-3. Factors that influence the nonradiological health effects incurred by repository workers.

hydrologic conditions; hydrologic conditions causing mine flooding (16); tectonic activity (19); the number of waste packages (8), which determines the volume of rock to be mined and the number of packages to be emplaced, thereby affecting the number of opportunities for accidents; physiological stress (9), which affects the number of human errors; and the number of accidents per operation for all operations (7). Hydrologic conditions are influenced by meteorology (18), such as local rainfall, and subsurface conditions (17), such as transmissivity. Physiological stress can be caused by high underground temperatures (10) and hydrologic conditions that lead to high humidity (16).

Surface fatalities and injuries. The number of surface fatalities and injuries (3) is determined by the rate of surface accidents (7) and the number and the distribution of surface workers (8). Surface accidents may be caused by severe weather (18) and tectonic events (19). Also as explained in Appendix F, a constant accident rate has been assumed.

Chronic illnesses and fatalities. The number of chronic illnesses and fatalities (4) is influenced by the presence of gases (15), which can cause illnesses. The presence of gases is influenced by the gas content of the rock (17) and mining techniques (14). Chronic health effects can also be caused directly by rock dust, which is also influenced by the rock characteristics and mining techniques.

E.1.4 PERFORMANCE OBJECTIVE 4

Performance objective and performance measure

This performance objective is to minimize the nonradiological health effects experienced by the public and attributable to the facility. The performance measure is nonradiological health effects in members of the public.

Influence diagram

The diagram is shown as Figure E-4 and is described below.

The nonradiological health effects that are experienced by the public and are due to the facility (1) depend on the deterioration of incremental air quality (2) and the functional relationship (3) between air quality and health effects (i.e., the numbers of illnesses and deaths caused by particular levels of air pollutants). The deterioration of air quality is caused by emissions from the facility (4).

Emissions attributed to the facility (4) can come from a number of sources. Among them are the exhaust gases emitted by the vehicles used by workers commuting to the site; this depends on the number of workers (5) and the commuting distance (6). Another source of emissions is the combustion equipment used in mining and surface construction (7). The quantity of exhaust gases released by such equipment depends on mining techniques (9) and the surface alterations necessary (10), which depend on rock characteristics (11) and surface features (12), respectively. Another source of emissions is fugitive dust (8), caused by mining (9) and surface alterations (10).

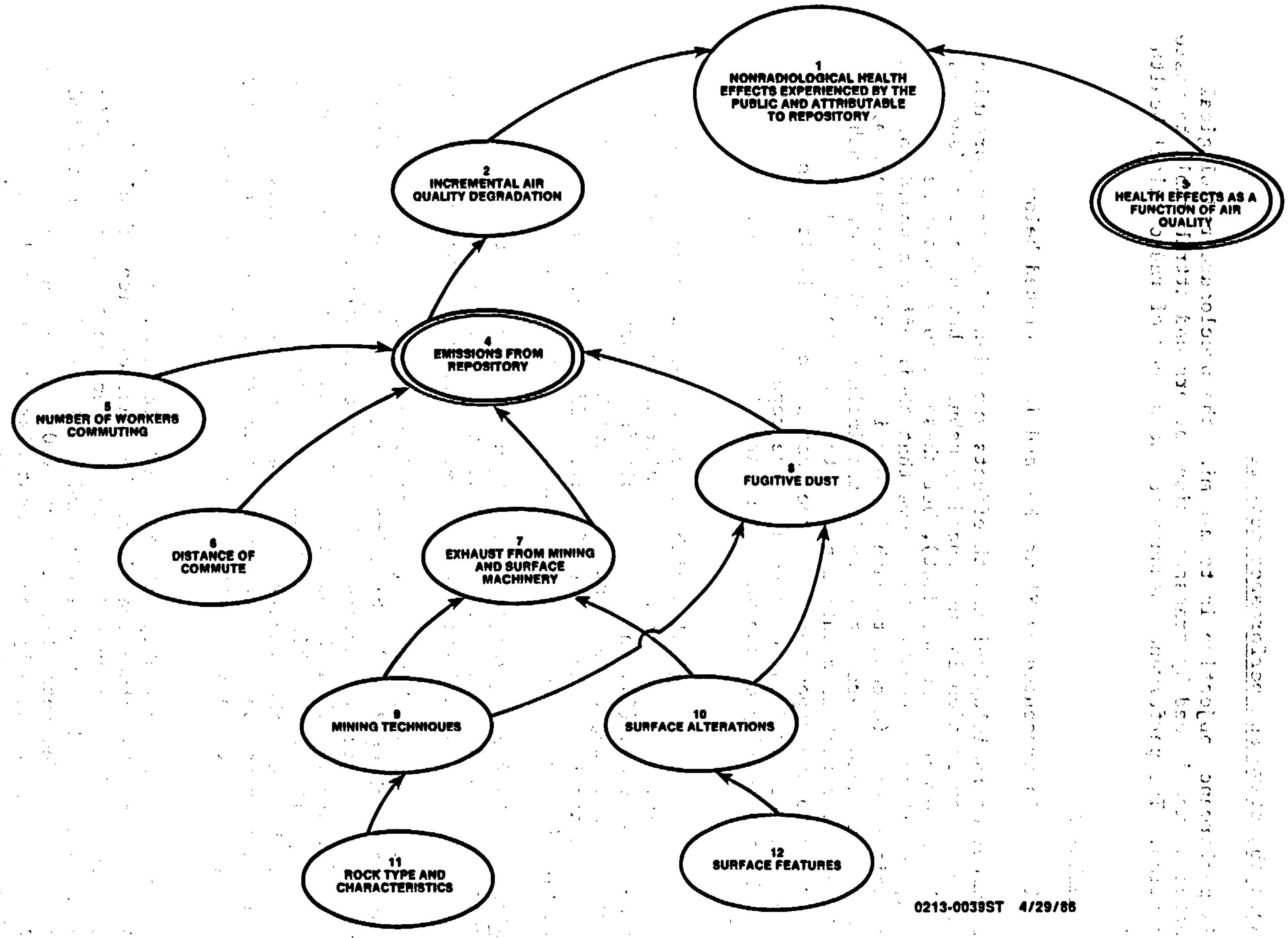

Figure E-4. Factors that influence the nonradiological health effects incurred by the public.

E.1.5 PERFORMANCE OBJECTIVE 5

Performance objective and performance measure

This performance objective is to minimize the preclosure radiological health effects experienced by transportation workers and attributable to waste transportation. The performance measure is the number of radiological health effects.

Influence diagram

The diagram is presented as Figure E-5 and is described below.

The number of radiological health effects experienced by transportation workers from transportation is influenced by nebulous human factors (such as responses in the event of an accident), but these factors cannot be quantified, and it is reasonable to assume that their effects would not depend on the repository site (except through factors in the influence diagram). Therefore, human factors are not shown in the influence diagram. Another contributive factor that is quantifiable is the truck/rail mix used to transport waste to the repository. It does not appear explicitly in the diagram because the mix does not depend on the repository site; it is determined by the ability of the waste generator to use each mode of transportation.

The preclosure radiological health effects experienced by transportation workers can be divided into health effects attributable to transportation under normal conditions (2), which may result from exposure to radiation from the shipping cask during transportation and health effects that may occur as a result of accidents (3). The number of health effects from normal transportation far outweighs those from accidents for all sites.

Health effects from normal transportation. The number of health effects that result from normal transportation is the product of the number of health effects per shipment (4) and the total number of shipments that are made (5).

The total number of shipments (5) depends on cask capacity(15) and the total waste to be shipped (16), which includes defense high-level waste and spent fuel from commercial reactors. The number of shipments from commercial reactors is far greater than the number of shipments of defense high-level waste. The capacity of the shipping cask depends on whether a truck or a rail cask is used. However, the truck/rail mix depends on the abilities of individual reactors to use these transport modes, and not on the repository site. Hence, the truck/rail mix itself is not a discriminating factor for siting.

The health effects per shipment (4) can be incurred at stops along the route (6) or during the actual transit of the transportation vehicle (a). At stops, the health effects incurred by workers depend on the crew size (14), the total duration of the exposure (7), and the level of radiation emitted from the cask (8). The total time at stops (10) depends on the total transit time (17), which is effected by the shipment distance (13) and the speed of travel (11). The health effects that are incurred in transit (9) depend on the total time the shipment is in transit (10), the crew size (11), and the level of radiation emitted from cask (8).

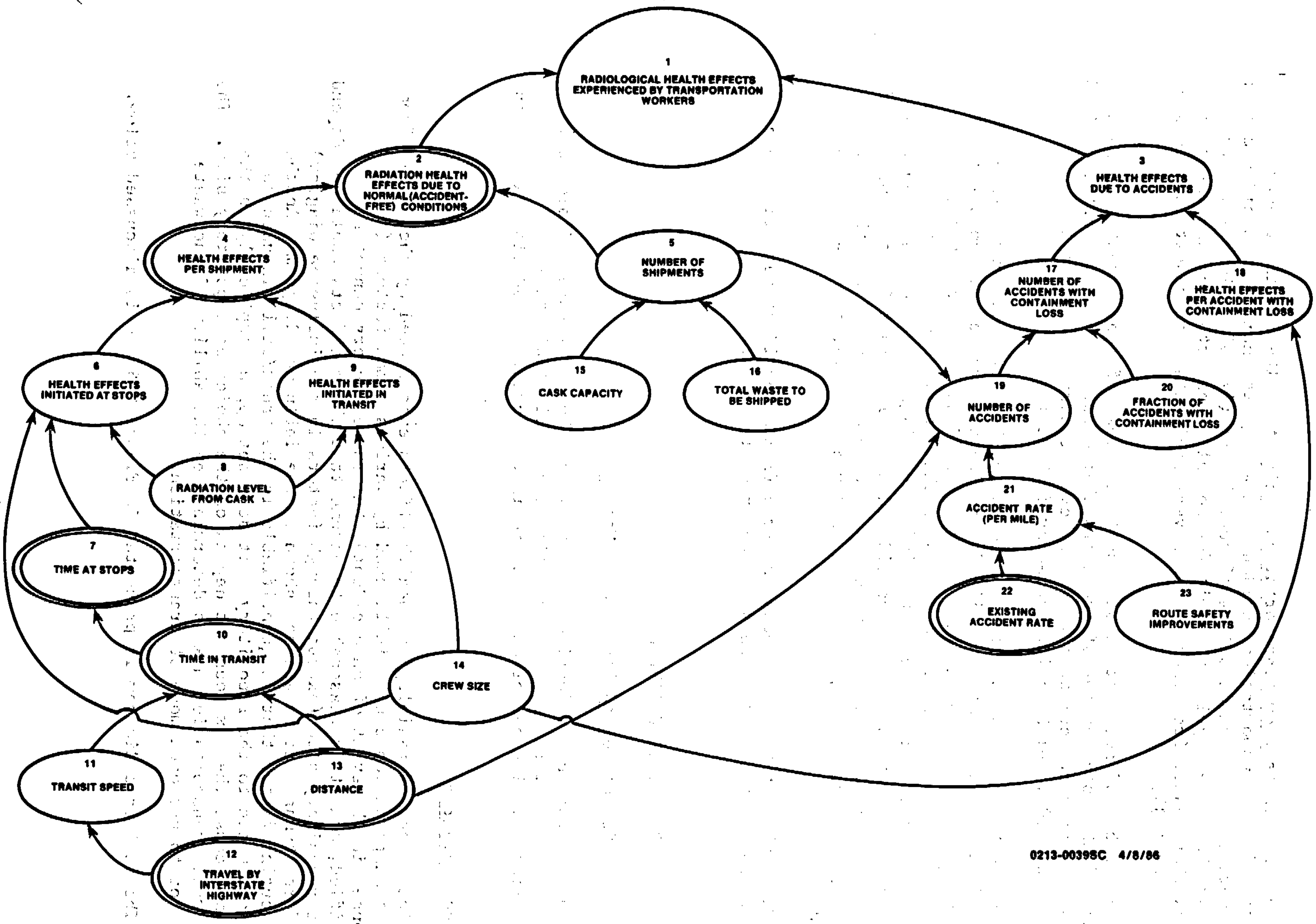

Figure E-5. Factors that influence the radiological health effects incurred by transportation workers.

Health effects from transportation accidents. The health effects resulting from transportation accidents depend on the number of accidents that are severe enough to cause a loss of containment (17) of radioactivity from the cask above the regulatory limit for normal transportation; and the health effects that result from each of the severe accidents that result in a loss of containment (18).

The number of accidents that result in a loss of containment (17) is the product of the total number of accidents that occur during transportation (19) and the fraction of accidents that are severe enough to cause a loss of containment (20), which is influenced by cask design.

The number of accidents is the product of the total distance traveled (13) and the accident rate per mile for radioactive waste shipments (21); this accident rate depends on (22) the existing accident rates for shipments in general commerce (22) and improvements to the safety condition of the routes (23). The factors presented on the influence diagram are not an exhaustive list, but represent those items considered to be important for the purpose of repository siting. It is recognized that there are other items that may affect accident rates (e.g., the time of day of travel), but these are not site dependent.

The number of health effects incurred from an accident resulting in a loss of containment (18) depends on the crew size (14).

E.1.6 PERFORMANCE OBJECTIVE 6

Performance Objective and Performance Measure

This performance objective is to minimize the preclosure radiological health effects experienced by the public and attributable to waste transportation. The performance measure is the number of radiological health effects.

Influence diagram

The number of radiological health effects experienced by the public from waste transportation can be influenced by various human factors (e.g., responses in the event of an accident), but these factors cannot be quantified, and it is reasonable to assume that their effects would not depend on the repository site (except through factors in the influence diagram). Therefore, human factors are not shown in the influence diagram. Another contributing factor that is quantifiable is the truck/rail mix used to transport waste to the repository. It does not appear explicitly in the diagram because the mix does not depend on the choice of repository site. The truck/rail transportation mix is determined by the ability of the waste generator to use each mode of transportation.

The influence diagram is presented in Figure E-6 and is discussed below.

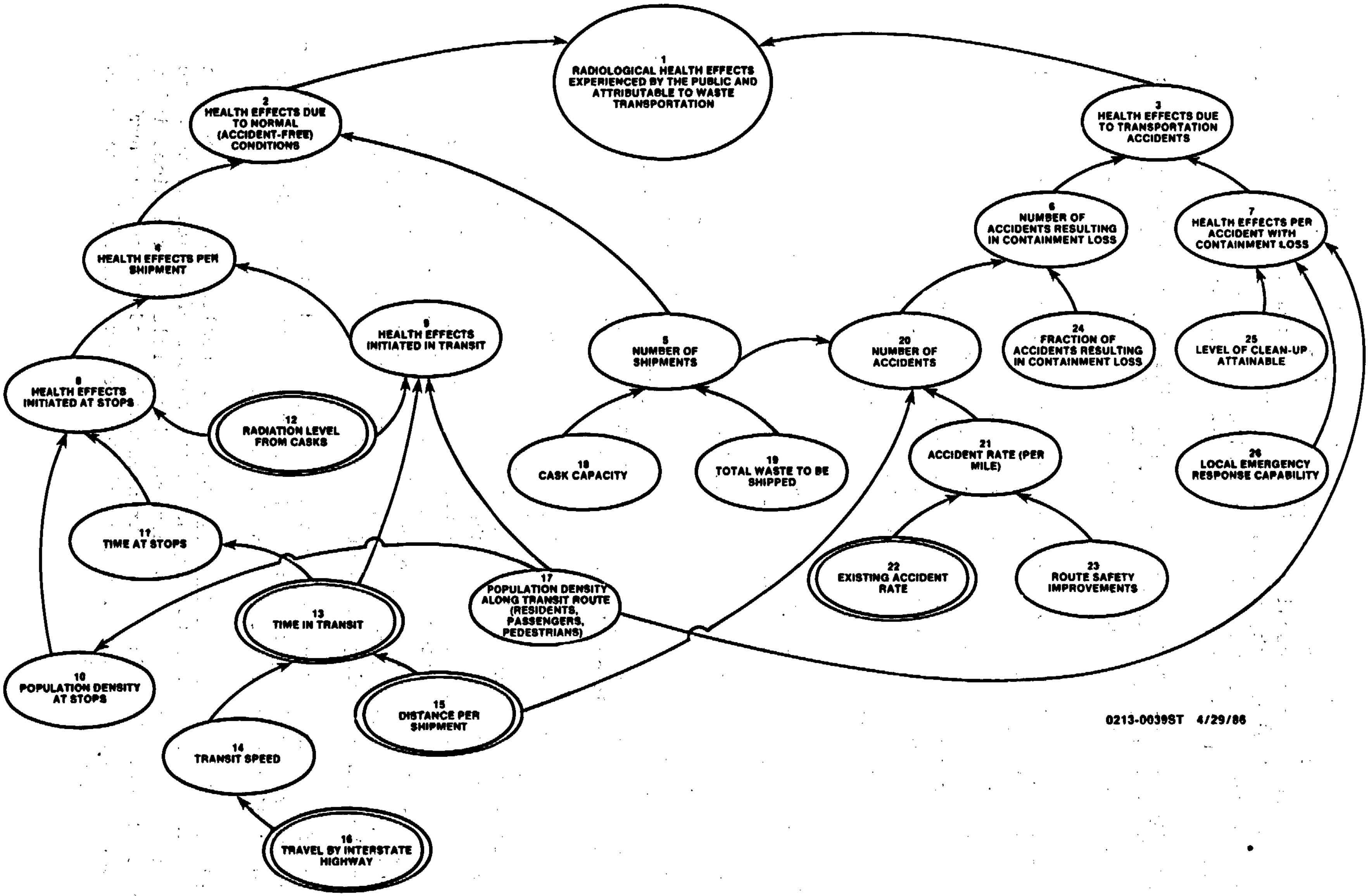

Figure E-6. Factors that influence the radiological health effects incurred by the public from waste transportation.

Preclosure radiological health effects experienced by the public from transportation (1) can be divided into (2) the health effects incurred from transportation under normal conditions (2), which may result from exposure to radiation from a shipping cask, and the health effects that may be incurred as a result of accidents (3). The number of health effects from normal transportation far outweigh those from accidents for all sites.

Health effects from normal transportation. The number of health effects incurred by the public from normal transportation (2) is the product of the health effects per each shipment (4) and the total number of shipments that are made (5).

The total number of shipments (5) depends on cask capacity (18), and the total quantity of defense high-level waste and spent fuel from commercial reactors to be shipped. The number of shipments from commercial reactors is far greater than the number of shipments of defense high-level waste. The capacity of the transportation cask (18) depends on whether a truck or rail cask is used. However, the truck/rail mix depends on the abilities of individual reactors to use these transportation modes, and not on the repository site. Hence, the truck/rail mix is not a discriminating factor for siting.

The health effects per shipment can be incurred at stops along the route (8) or during the actual transit of the transportation vehicle (9).

At stops, the number of health effects incurred by the public depends on the population density (10) at stops like truck stops, weigh stations, and rail yards, the total duration of the exposure (11), and the level of radiation emitted from the cask (12). The population exposed at stops (10) is related to the population along the transportation route (17), and the total time at stops (11) depends on the total transit time (13).

The total time spent in transit (13) depends on the shipment distance (15) and the transit speed (14). Transit speed depends on the amount of travel by interstate highway (16). The portion of truck travel by Interstate highway that occurs in the region of the repository site (the "minimum transportation study area" that is discussed in Section 6.2.1.8 of the EAs) is a discriminating factor. Interstate highway travel is important because it is expected that considerably fewer people will be exposed along Interstate highways than along other routes, because of the generally wider right-of-way and distance between opposing lines of traffic.

Health effects that occur during transit (9) depend on the total time the shipment is in transit (13), the population along the transit route (17), and the level of radiation of emitted from the cask (12).

Health effects from transportation accidents. Health effects resulting from transportation accidents (3) depend on the number of accidents that are severe enough to cause a loss of containment with a release of radioactivity above the regulatory limit for normal transportation and the average number of health effects (7) that result from each of those severe accidents that result in a loss of containment (6).

The number of accidents that result in a loss of containment (6) is the product of the total number of accidents that occur during transport (20) and the fraction of accidents that are severe enough to cause a loss of containment (24), which depends on the design of the cask.

The number of accidents (20) is the product of the total distance the shipment travels (15) and the accident rate per mile for radioactive-waste shipments (21). The accident rate for shipments of radioactive waste depends on the existing accident rates for shipments in general commerce (22) and improvements to the safety condition of the routes (23). The factors presented on the influence diagram are not an exhaustive list, but represent those items considered to be important for the purpose of repository siting. It is recognized that there are other items that may affect accident rates (e.g., time of day of travel), but they are not site dependent.

The health effects that result from an accident resulting in containment loss (7) depend on the population that is at risk from that accident (17), the level of clean up that is attainable after the accident (25), and the emergency-response capability near the accident.

E.1.7 PERFORMANCE OBJECTIVE 7

Performance objective and performance measure

The performance objective is to minimize the preclosure nonradiological health effects experienced by transportation workers and attributable to waste transportation. The performance measure is the number of worker fatalities.

Influence diagram

The diagram is shown as Figure E-7 and is described below. The number of nonradiological health effects experienced by transportation workers from transportation (1) is the product of the total number of waste shipments (4), the fraction of those shipments that result in an accident (2), and the number of health effects, in terms of worker deaths and injuries, that will occur per accident (3). Nonradiological health effects do not depend on the radioactivity of the cargo; they are similar to the effects that would occur in any truck or rail accident, whatever the commodity being transported.

The number of accidents that would occur in any shipment of waste to the repository (2) depends on the accident rate per mile for radioactive-waste shipments (5) and the distance traveled (6).

Because rail routes and highway routes are often of different lengths from origin to destination, the distance per shipment depends on the mix of the truck and rail modes (14). The truck/rail mix depends on the ability of individual reactors to use these transportation modes, and not on the repository sites. Truck/rail mix itself is not a discriminating factor for siting.

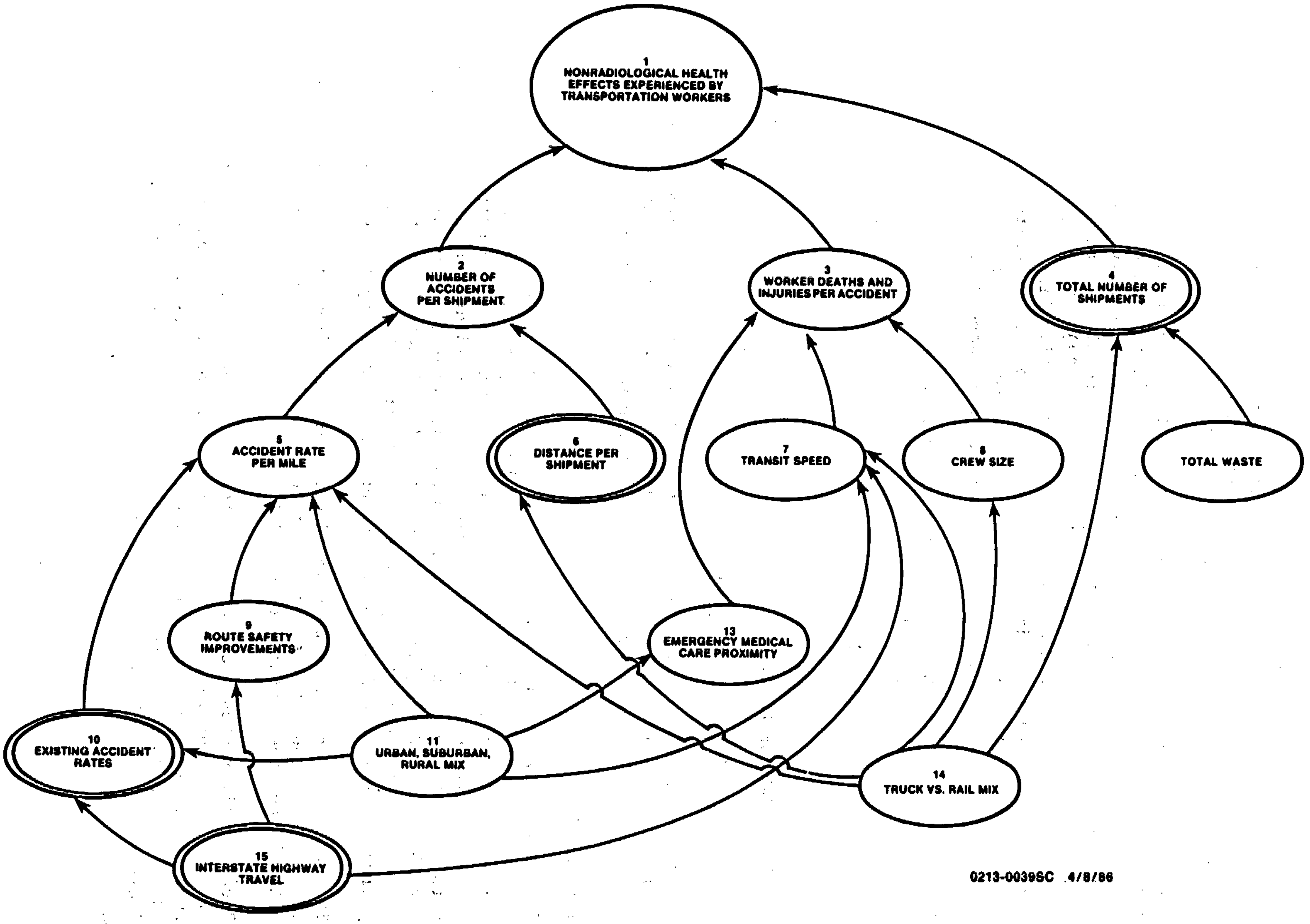

Figure E-7. Factors that influence the nonradiological health effects incurred by transportation workers.

The accident rate for radioactive-waste shipments (5) depends on the existing accident rates for shipments in general commerce (10); the mode of shipment (14), truck or rail; and the population density of the area through which the shipment travels (11). There are also other factors that may influence the accident rate for waste shipments such as (9) improvements in the safety condition of the routes (8), but they are not readily quantifiable. The factors presented on the influence diagram are not an exhaustive list; they represent the items considered to be important for the purpose of repository siting. It is recognized that there are other factors that may affect accident rates (e.g., the time of day when travel occurs), but they are not site discriminators.

Since rail casks and truck casks are of different sizes, they carry a different number of spent-fuel assemblies. The mix of truck and rail modes (14) and the total quantity of waste (14) are the factors that determine the total number of shipments (4).

The severity of the consequences of an accident, in terms of deaths and injuries in transportation workers (3), depends on the speed at which the vehicle is traveling (7); the number of workers at risk, which is the crew size (8); and proximity to emergency care facilities (13). The type of area (e.g., urban, suburban, rural) in which an accident occurs (11) may affect proximity to emergency medical facilities (13).

The speed at which the vehicle travels (7) varies between trucks and trains and through urban, suburban, and rural areas. For trucks the speed is also affected by the portion of travel that is by Interstate highway (15).

E.1.8 PERFORMANCE OBJECTIVE 8

Performance objective and performance measure

This performance objective is to minimize the preclosure nonradiological health effects experienced by the public and attributable to waste transportation. The performance measure is the number of accident fatalities.

Influence diagram

The influence diagram is shown as Figure E-8 and is discussed below.

The number of nonradiological health effects experienced by the public from transportation is the product of the total number of waste shipments (4), the fraction of those shipments that result in an accident (2), and the number of health effects, in terms of deaths and injuries, that will occur per accident (3). Nonradiological health effects do not depend on the radioactivity of the cargo; they are similar to the effects that would occur in any truck or rail accident, whatever the commodity being transported. Although the public would incur some health effects from the pollutants emitted by the transport vehicles, these effects are not considered because they would occur almost exclusively in urban areas and are quite small in comparison with accident effects.

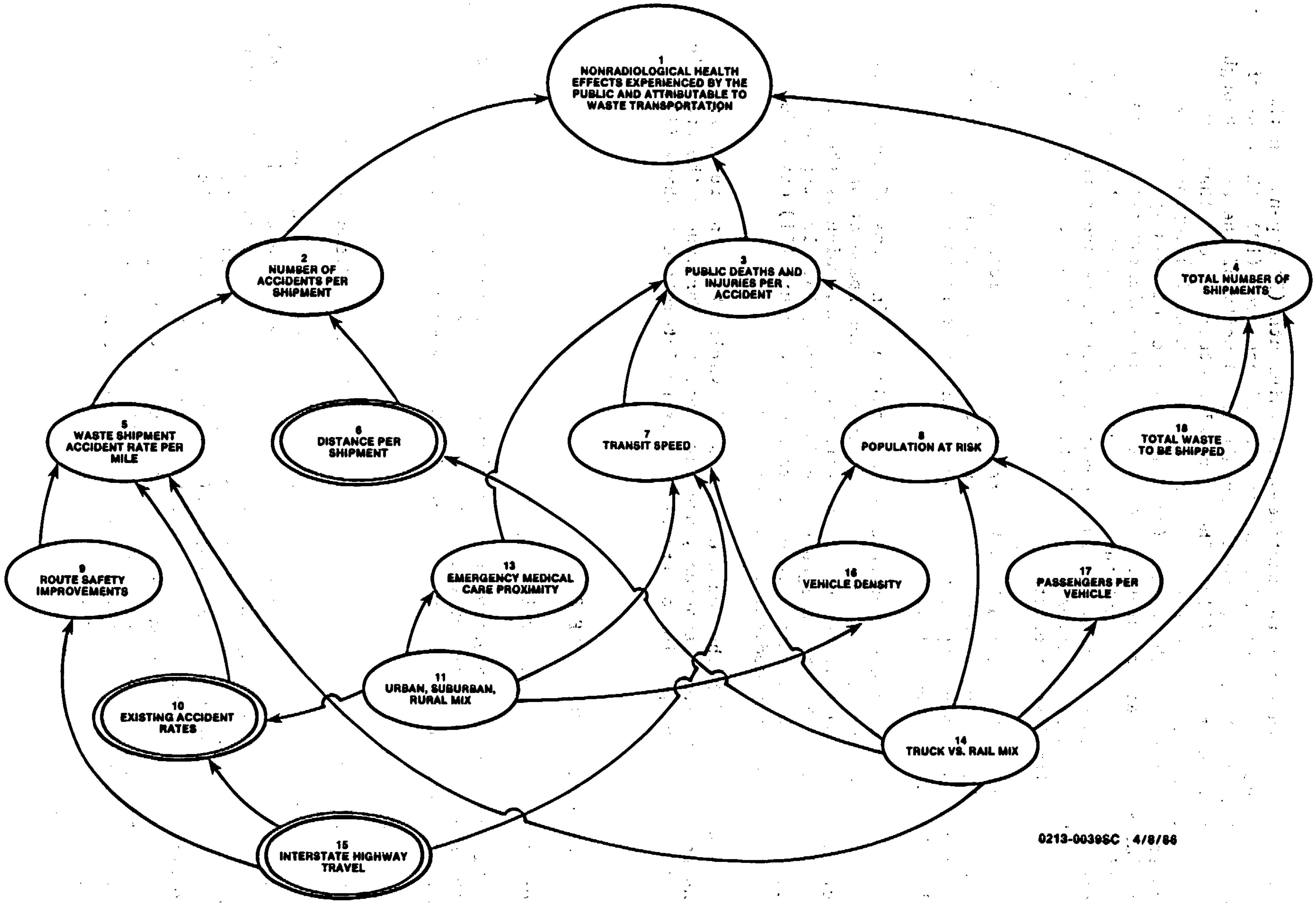

Figure E-8. Factors that influence the nonradiological health effects incurred by the public from waste transportation

The number of accidents that would occur in any shipment of waste (2) is the product of the accident rate per mile for radioactive-waste shipments (5) and the distance traveled (6).

Because rail routes and highway routes are often of different lengths from origin to destination, the distance per shipment depends on the mix of truck and rail modes (14). It should be emphasized that truck/rail mix depends on the abilities of individual reactors to use these transport modes, and not on the repository site. The truck/rail mix itself is not a discriminating factor in repository siting.

The accident rate for waste shipments depends on the existing accident rates for shipments in general commerce (10); the mode of shipment (14), truck or rail; and the population density of the area through which the shipment travels (11). There are also other factors that may influence the accident rate for shipments to the repository, but they are not readily measurable; an example is improvements in the safety condition of the routes (9). The factors presented on the influence diagram are not an exhaustive list,but represent the items considered to be important for the purpose of repository siting. It is recognized that there are other items that may affect accident rates (e.g., the time of day when travel occurs), but they are not site discriminators.

Since rail casks and truck casks are of different sizes, they carry a different number of spent-fuel assemblies. The mix of truck and rail modes (14) and the total waste (18) are the factors that determine the total number of shipments (4).

In any one accident some members of the public (8) are at risk of being injured or killed. The number is determined by the number of passengers in other vehicles involved in the accident (17); the mode of shipment, by rail or highway; and, for a truck accident, the density of vehicles on the road (16), which differs in urban, suburban, and rural areas (11). In addition to accidents involving the same type of vehicle (e.g., a train carrying waste and a passenger train or a truck carrying waste and a passenger car), other types of accidents are possible. These could include pedestrians or grade crossings.

The severity of the consequences of an accident, in terms of deaths and injuries to the public (3), can depend on the speed at which the transport vehicles is traveling (7). The type of area (i.e., urban, suburban, rural) in which an accident occurs may also influence proximity to emergency medical care (13). Proximity to emergency medical facilities can affect the outcome of an accident.

The speed at which the transport vehicle travels varies between trucks and trains, and among types of areas (urban, suburban, and rural). It is also affected by the portion of travel that is by Interstate highway (15).

E.2 ENVIRONMENTAL IMPACTS

There are three objectives related to the minimization of environmental impacts; they are concerned with aesthetics impacts; archaeological, historical, and cultural impacts; and biological impacts. Both the effects from the repository facility itself and from waste transportation are considered within each objective.

E.2.1 ENVIRONMENTAL PERFORMANCE OBJECTIVE 1

Performance objective and performance measure

This performance objective is to minimize the degradation of aesthetic qualities attributable to the repository and waste transportation.

Since there is no readily quantifiable measure for the degradation of aesthetic qualities that is attributable to the repository and waste transportation, the performance measure addresses degradation on a scale of effects from "none" to "major" aesthetic effects.

The EAs contain the data and analyses pertinent to this particular objective. Sections 4.2.1 and 5.2 of the EAs describe the effects on aesthetic quality from site characterization activities and from repository construction, operation, and decommissioning, respectively. Section 6.2.1.6 evaluates each particular site against the technical guideline on environmental quality.

Influence diagram

The diagram is shown as Figure E-9 and is described below.

The degradation of aesthetic qualities (1) is caused by visual changes (2) and incremental noise (3); it is influenced by the aesthetic sensitivity of the resource (4) the uniqueness of the resource area (5), and the affected population (6). (It is worse to affect a unique area because the same aesthetic qualities cannot be experienced elsewhere.)

Visual changes (2) are changes in lighting (7), color (8), and form (9). These are caused by new structures (10) and alterations of the land surface (11); they depend on the distance between the aesthetic resource and the facility (12).

Incremental noise sources (3) are transport vehicles (13), construction equipment for both excavation and surface construction (15, 17, 18) and repository operations (14). The level of noise is affected by the noise-transport characteristics of the site (19), which include buffers.

The terrain of the site (16) will determine the surface alterations (11) that are necessary, the construction equipment that is used (15), and the existing visual setting (22).

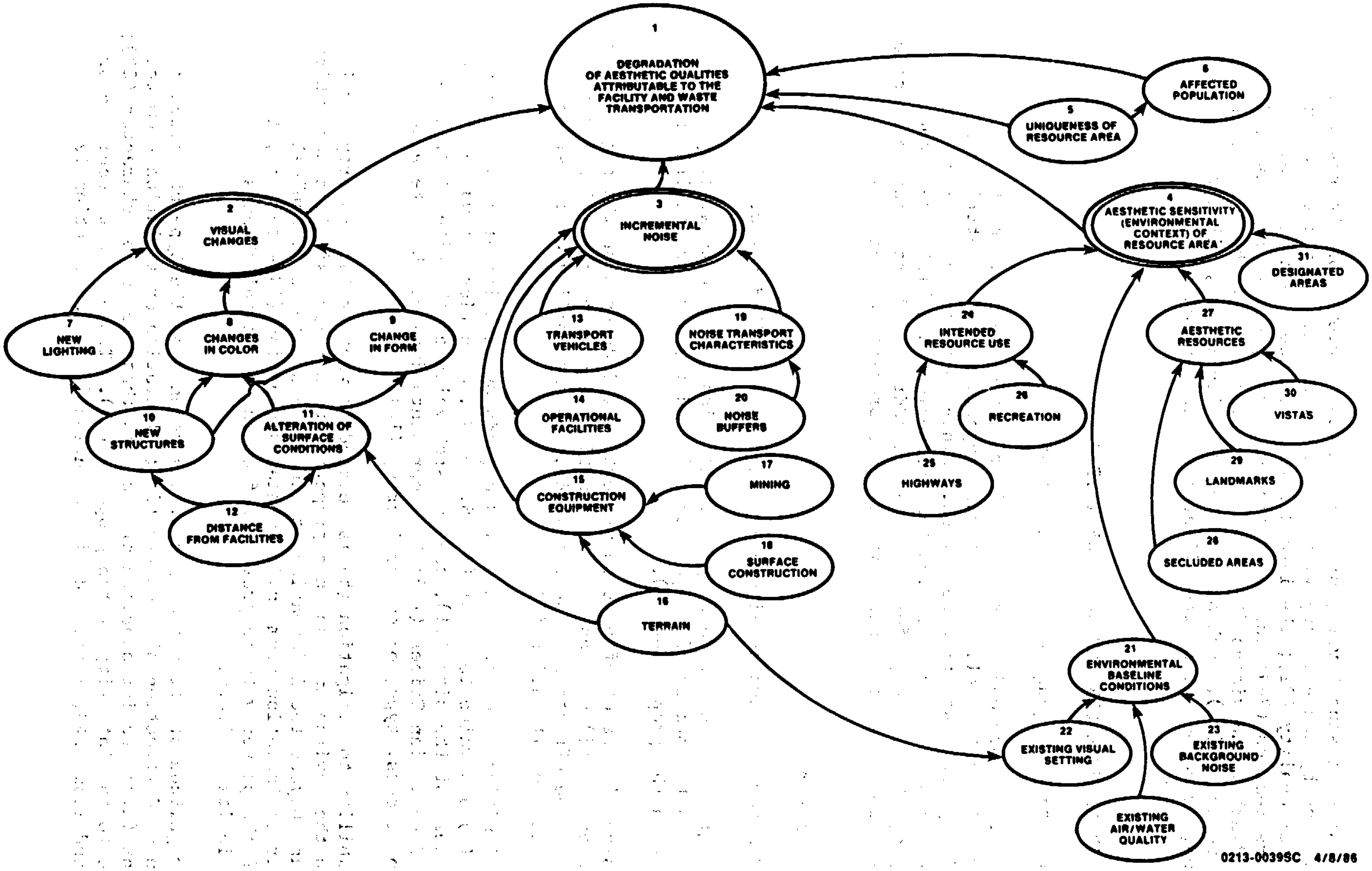

Figure E-9. Factors that influence the degradation of aesthetic quality.

The aesthetic sensitivity, or environmental context, of the resource area (4) is affected by the existing visual setting, background noise and ambient air and water quality (21); the intended resource use, such as scenic highways, recreation (24); the aesthetic resources present, such as secluded areas, landmarks, and vistas (27); and the designation of the area as an aesthetic resource (31), such as a State or National Park, wildlife refuge, forest land, or component of the wilderness preservation system.

E.2.2 ENVIRONMENTAL PERFORMANCE OBJECTIVE 2

Performance objective and performance measure

This performance objective is to minimize the degradation of archaeological, historical, and cultural properties that is attributable to the repository and waste transportation. Since there is no readily quantifiable measure of degradation for archaeological, historical, and cultural properties, the performance measure addresses degradation on a scale of effects from "none" to "major impacts on a property of national significance."

Influence diagram

The diagram is shown as Figure E-10 and is described below.

The degradation of archaeological, historical, and cultural properties (1) depends on the number of properties affected (2) and the significance of the effects on the properties (3).

The significance of effects on properties (3) depends on the significance of the properties (3) depends on the significance of the properties (4) the magnitude of the effects on properties (6), and amenability of the effects on the properties to mitigation (5).

The significance of properties (4) depends on classification in various registers (7) and value to local (8), State (9), or national (10) populations; the uniqueness of the site (11); the research value of the site (12); treaty rights held by Indian Tribes (13); the representatives of the site with respect to process, type, or cultural group (14).

Amenability to mitigation (5) is related to whether the property's value depends on the environment (as in a property of religious significance, which is important beyond the information it contains) and to the technical feasibility of isolation from environmental disruption (19)--that is, the ability of the property to be protected from environmental changes or excavated in its entirety.

The magnitude of effects on properties depends on the type of effects: alteration or destruction of property (20); alteration or isolation from the environment (21); the introduction of elements that are out of character (22); and damage to the integrity of the property (23). Those effects could occur through vandalism (24), increased air pollution (25), construction (26),

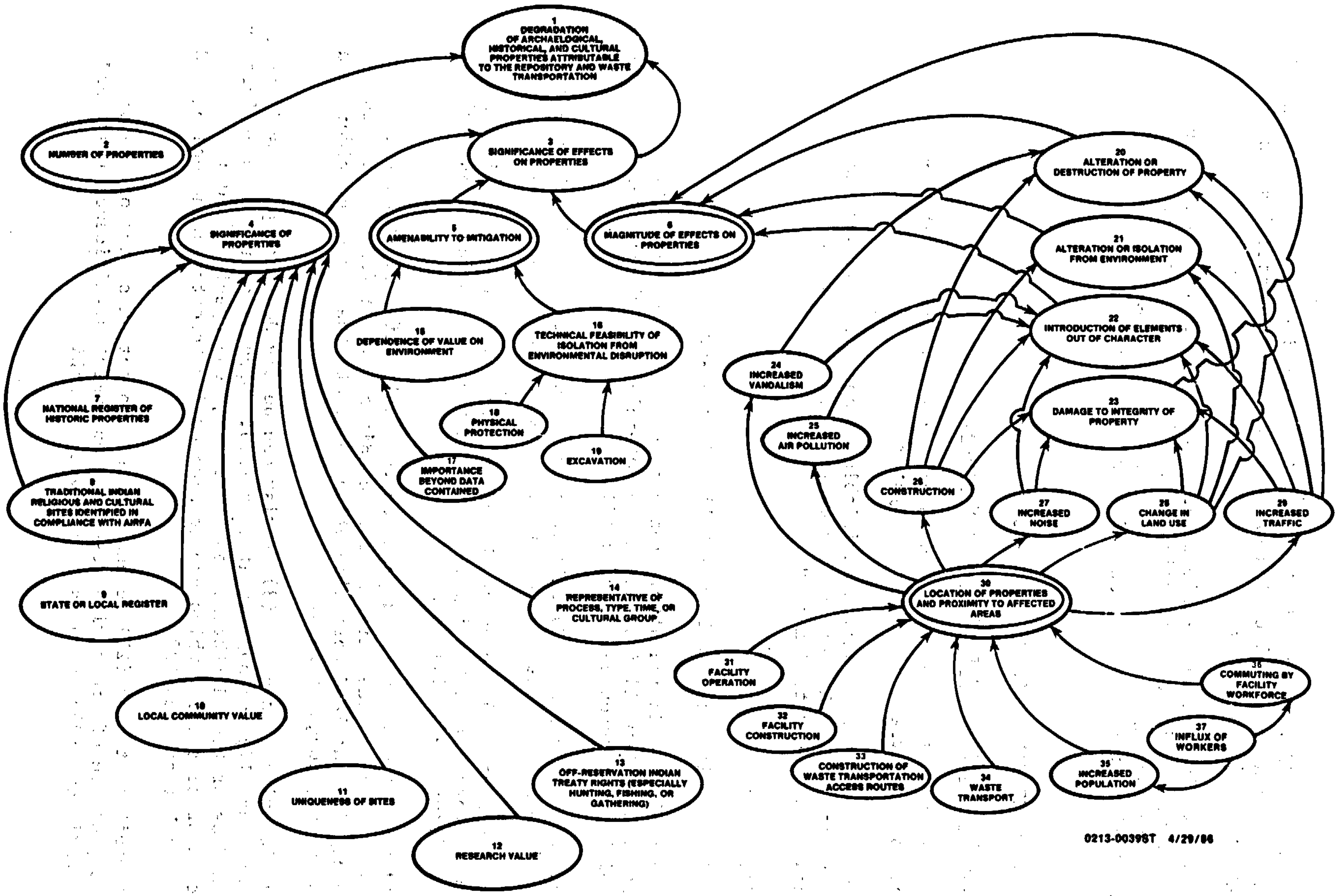

Figure E-10. Factors that influence the degradation of archaeological, historical, and cultural properties.

increased noise (27), changes in land use (28), and increases in traffic (29), all of which depend on the location of the significant properties and proximity to the affected areas.

The areas affected and proximity of properties to these depend on repository construction and operation (31, 32), access-route construction (33), the transportation of waste (34), and the increased population (35) and commuting (36) that result from an influx of workers (37).

E.2.3 ENVIRONMENTAL PERFORMANCE OBJECTIVE 3

Performance Objective and Performance Measure

The objective is to minimize the biological degradation attributable to the repository and the transportation system.

Since there is no readily quantifiable measure for the degradation of biological resources, the performance measure addresses degradation on a scale of effects from "none" to "major."

Influence diagram

The diagram is shown as Figure E-11 and is described below.

Biological degradation attributable to the repository and the transportation system (1) depends on project-related environmental changes (2) and the biological resources at risk (3).

Environmental changes (2) fall into three categories: direct effects (4), land-form alterations (5), and project-related emissions (6).

Direct effects (4) are caused by water withdrawals (7); traffic (80), which causes road kills; hunting (9), and traffic in resource areas (10), which can disturb sensitive species.

Land-form alteration (5) depends on the design of facilities and access corridors (11) and on the existing land conditions (12); for example, there would be significant land-form alteration to create the access corridor at a site with a very rough terrain.

The biological resources (3) at risk can be divided into plant and animal species at risk (17) and habitat at risk (21). Species at risk can be further categorized as protected (threatened and endangered) species (180); significant species (19), which are considered for threatened and endangered status; or other species (20).

The habitat at risk (21) depends on the protection status of the area (22), the presence of areas with resource-management significance (24), and habitat conditions (23), such as sensitivity of habitat.

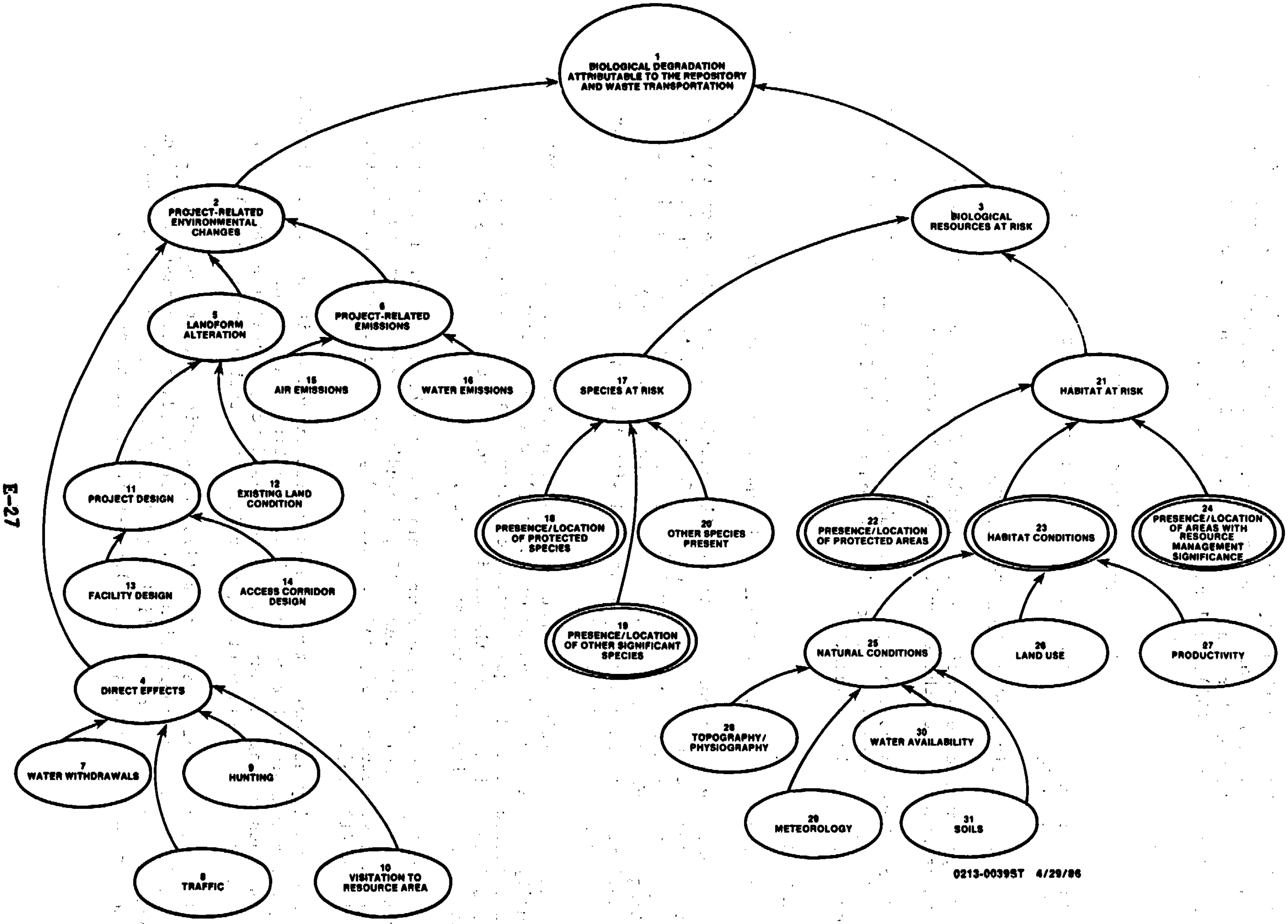

Figure E-11. Factors that influence biological degradation.

Habitat conditions (23) depend on the productivity of the land (27); land use (26), such as recreational land use; and natural conditions (28) -- that is, the combination of terrain and physiography (28), meteorology (29), the availability of water (30), soil characteristics (31).

E.3 SOCIOECONOMIC IMPACTS

This section discusses the socioeconomic impacts of the repository and waste transportation.

Performance objective and performance measure

The performance objective is to minimize the adverse socioeconomic impacts attributable to the repository and waste transportation.

Since there is no readily quantifiable measure of socioeconomic impacts, the performance measure addresses impacts on a scale from "no impacts" to "major socioeconomic impacts."

Influence diagram

The diagram is shown as Figure E-12 and is described below.

The adverse socioeconomic effects (1) attributable to the repository and waste transportation are of two types: effects due to the incompatibility of the repository with the community (2) and effects due to the inability of the existing structure to deal with repository-induced growth (3). Incompatibility effects can be associated with lifestyles and values (4) or with land use and ownership (5).

All compatibilities and inadequacies arise from the interactions between community structures and characteristics (8) and repository- and transportation-related requirements, contributions, and characteristics. It is this interaction between the project and the existing community that causes positive or negative socioeconomic effects.

Community structures and characteristics can be categorized as economic structure (10); social structure (15), including lifestyles and values; demographic structure (16); and private and public facilities and service structures (17, 18).

A community economic structure is characterized by its economic diversity (14); water and mineral resources (11); existing and planned land uses (12), such as industry, agriculture, commerce, residence, recreation, and tourism; and current land ownership (13) (Federal, State, tribal, or private).

Private and public facilities (17) and service structures (18) are housing (22); the transportation infrastructure (24); government and fiscal structure (25); emergency facilities (26), such as fire protection, police protection, and hospitals; and public service infrastructure (27).

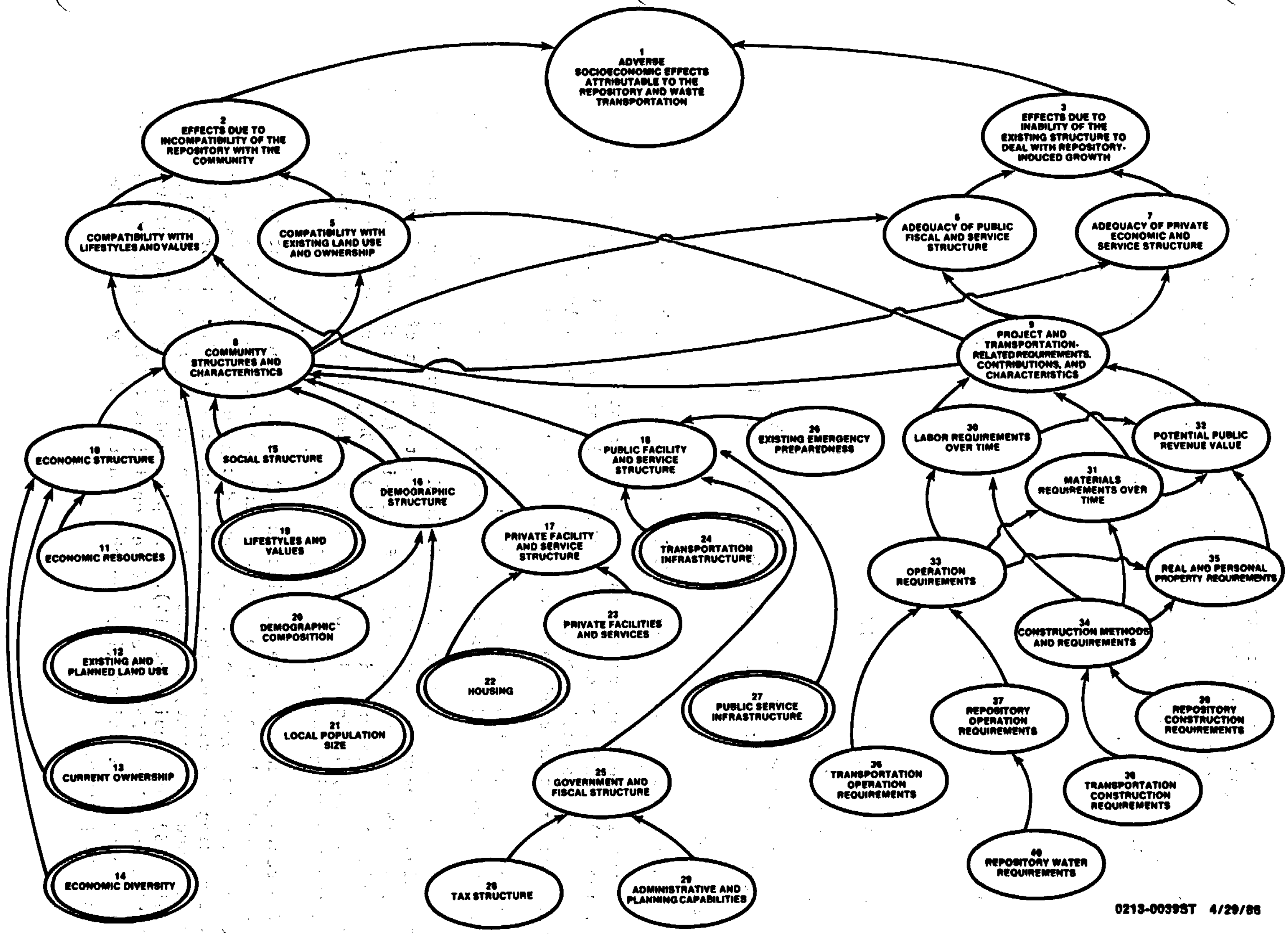

Figure E-12. Factors that influence adverse socioeconomic effects.

Repository- and transportation-related requirements, contributions, and characteristics (9) are requirements for labor (30) and materials (31). The construction and operation of the repository will create labor and materials demands, and the large influx of labor for the repository will create a demand for real and personal property, transportation facilities, and consumer goods and services. The repository will also contribute to the public revenues (32) (e.g., by increasing the tax base).

E.4 ECONOMIC IMPACTS

This section describes the costs attributable to the repository itself and to waste-transportation operations.

E.4.1 COST PERFORMANCE OBJECTIVE 1

Performance objective and performance measure

This performance objective is to minimize the cost of the repository. The performance measure is the cost in dollars (no discounting).

Influence diagram

The diagram is shown as Figure E-13 and is described below.

The total repository cost consists of the costs of development and evaluation (2), construction (3), operation (4), and decommissioning (5). Development and evaluation costs were assumed to start in 1983, and decommissioning is assumed to occur in approximately 80 years.

The cost of development and evaluation (2) consists of the cost of site characterization (6) and the cost of repository and waste-package design (7).

The cost of construction (3) is defined as the cost incurred during the construction category of the repository. The two types of cost in this category are the cost of the surface facilities (8) and the cost of mining and constructing the underground repository (18). Only a part of the total mining for the repository is done during the construction phase; the rest is done during the operating phase of the repository.

The costs of the surface facilities (8) consists of the cost of land acquisition (9) and the cost of constructing the surface facilities (10). Construction costs depend on the plan and design of the surface facilities (15), including the size of the work force and the required labor skills, materials, and equipment, and the unit cost of each type of labor (11), materials (13), and equipment (14). The plan and design of the surface facilities are also affected by surface conditions (12), such as the terrain (16) and weather conditions (17), which may affect the type of earth-moving that must be planned.

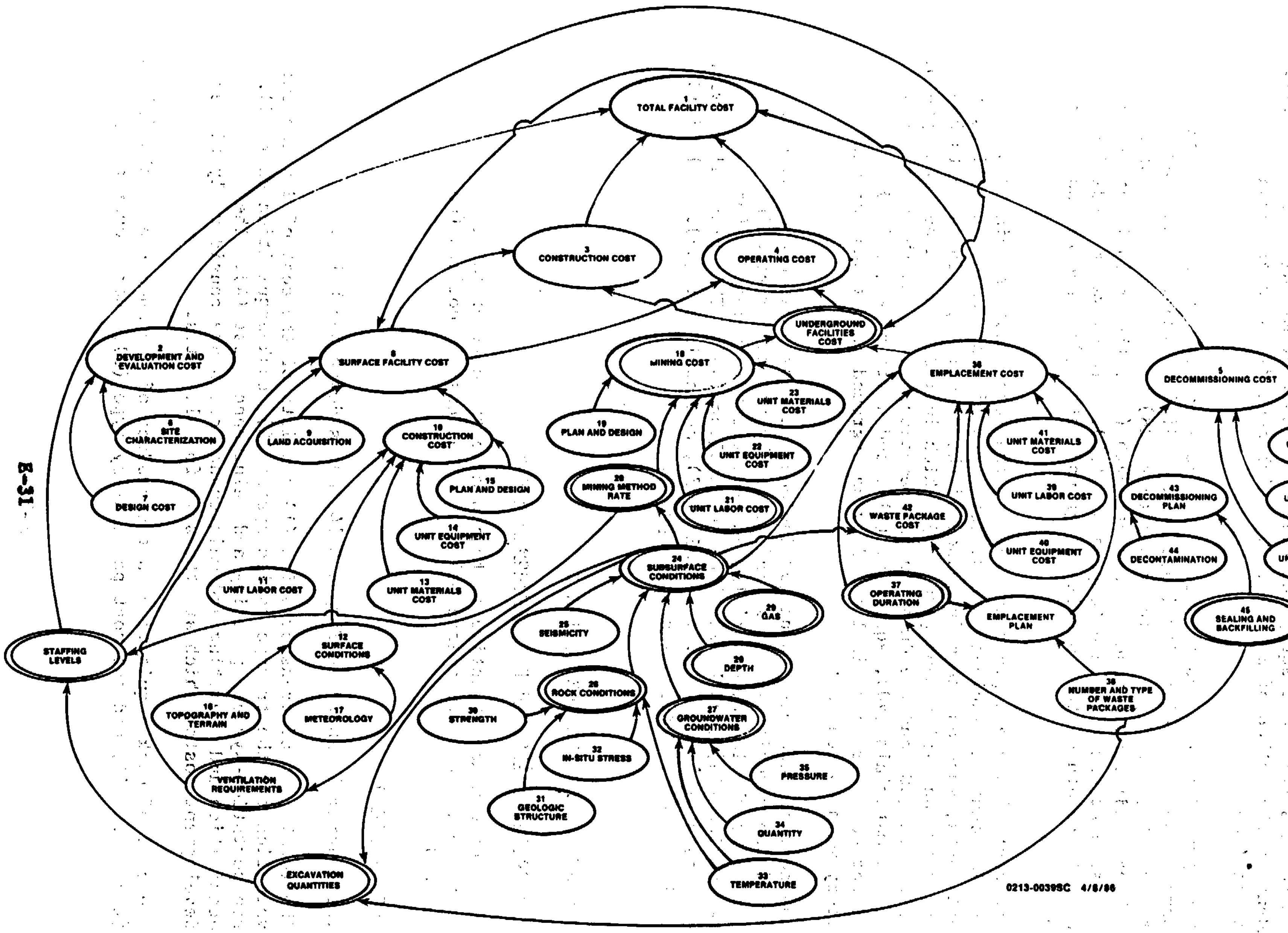

Figure E-13. Factors that influence the total cost of the repository.

The cost of mining (18) is the total cost of constructing the underground portion of the repository. It is affected by the mining plan and design (19), which includes labor, materials, and equipment, and the unit costs of labor (21), materials (22), and equipment (23). The cost of mining is also heavily dependent on the method of mining (20), which depends on underground conditions (24).

Underground conditions (24) covers various aspects of the host-rock environment, such as seismicity (25), rock conditions (26), ground-water conditions (26), the depth of the repository (28), and the presence of gas (29). Rock conditions depend on rock strength (30), the geologic structure (31), in-situ stress (32), and temperature (33). Ground-water conditions depend on temperature, the quantity of ground water (34), and ground-water pressure (35).

The cost of waste emplacement (36) is the total cost associated with waste emplacement; it includes the direct costs of emplacement as well as the indirect costs, such as the maintenance of the repository. These costs are influenced by the emplacement plan (49), which includes the number and type of waste packages (38) and the duration of operations (37), and the unit costs of labor (39), materials (40), equipment (41), and waste packages (42). Emplacement costs are also influenced by underground conditions through repository-maintenance costs.

The cost of decommissioning (5) includes all costs associated with the closure of the repository. It is influenced by the decommissioning plan (43), which includes the labor, materials, and equipment requirements for decontamination (44), and backfilling and sealing (45). This plan, along with the unit costs of labor (46), materials (47), and equipment (48), will yield the total cost of the decommissioning phase.

E.4.2 COST PERFORMANCE OBJECTIVE 2

Performance objective and performance measure

This performance objective is to minimize the cost of total transportation. The performance measure is the cost in dollars (no discounting).

Influence diagram

The diagram is shown as Figure E-14 and is described below.

The total cost of transportation (1) consists of the cost of development and evaluation for the transportation system (2), cask-acquisition cost (3), and transportation-system operating and maintenance cost (4). The cask-acquisition and operating and maintenance costs are considerably higher than development costs, which are the same for all sites.

The cost of cask acquisition is the product of the number of casks (5) by type (truck or rail) and the cost per cask by type (6), summed over types.

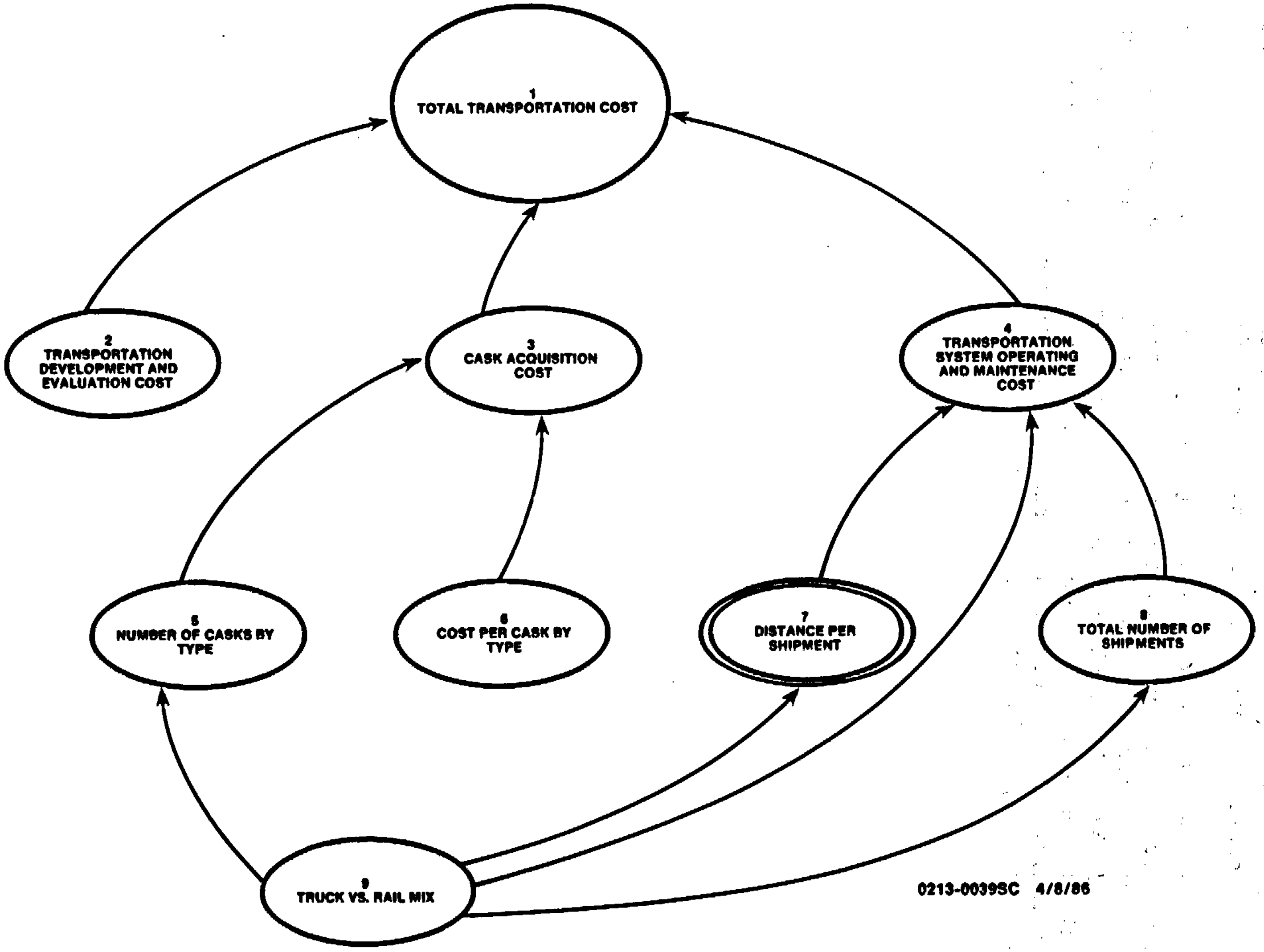

Figure E-14. Factors that influence total transportation costs.

The operating and maintenance cost of the transportation system (4) depends on the distance per shipment (7), the total number of shipments (8), and the truck vs. rail mix (9). The number of shipments is influenced by the truck/rail mix because the two types of casks have different capacities.

The distance per shipment (7) affects the time required for each shipment and thus the number of shipments a single cask can carry. Since the total number of shipments is constant, the distance per shipment affects the number of casks required (5). The truck/rail mix (9) determines how many casks of each are required. However, since the truck/rail mix depends only on the capability of individual reactors to use these transportation modes, and not on the repository site, it is not a site discriminator.

Appendix F

SITE RATINGS ON PRECLOSURE OBJECTIVES

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Appendix F

SITE RATINGS ON PRECLOSURE OBJECTIVES

Chapter 4 summarized the ratings assigned each site on each of the 14 objectives in the preclosure analysis. The purpose of this appendix is to present additional information on the basis for the site ratings. The appendix is organized according to the major categories of concern in the preclosure period--namely, health and safety (radiological and nonradiological effects incurred by the public or workers from the repository or waste transportation), environmental and socioeconomic impacts, and the costs of the repository and waste transportation.

F.1 HEALTH-AND-SAFETY OBJECTIVES

There are eight health-and-safety objectives, four each associated with the repository and with waste transportation. Two of the four objectives in each category are related to radiological safety, and the other two are related to nonradiological safety.

With regard to radiological-safety objectives, some discussion of the relationship of radiation doses to radiological effects is in order. Because any radionuclide releases are expected to be small and the radiation dose received by any individual will be small, the effects will be long-delayed somatic and genetic effects; they will occur, if at all, in a very small fraction of the persons exposed. Even in severe accidents involving larger doses, there is no possibility of an "acute" radiation effect that results in death within days or weeks. The effects that must be considered are (1) cancers that may eventually result from whole-body exposures and, more specifically, from radioactive materials deposited in the lung, bone, and thyroid and (2) genetic effects, which are reflected in future generations.

Knowledge of these delayed effects of low doses of radiation is necessarily indirect because their incidence is too low to be observed against the much higher incidence of similar effects from other causes. Thus, for example, it is not possible to attribute any specific number of human lung cancers to the plutonium present in everyone's lungs from weapons-test fallout because lung cancers are known to be caused by other materials present in much more hazardous concentrations and because lung cancers occurred before there was any plutonium. Even in controlled studies with experimental animals, one reaches a low incidence of effect indistinguishable from the level of effect in unexposed animals, at exposure levels far higher than those predicted to result from waste-management and disposal activities. Hence only a relationship between health effects and radiation doses can be estimated, basing this estimate on observations made at very much higher exposure levels, where effects have been observed in people, and on carefully conducted animal experiments.

The various dose-effect relationships and the models for projecting risks forward in time that have been proposed in the literature produce widely different estimates of the health effects from low radiation doses. A range of 50 to 500 premature deaths from cancer and 50 to 500 specific genetic effects in all generations per million man-rem encompasses the estimates in the published literature. A value of 280 fatal cancers (radiological fatalities) per million man-rem is used here in the preclosure analysis of the nominated sites. This value is in the upper range of the risk estimates and is the value the Environmental Protection Agency (EPA) used in developing the environmental standards for geologic disposal, 40 CFR Part 191 (EPA, 1985). Thus, the adoption of 280 fatal cancers as the risk factor ensures consistency with the postclosure analysis. This value is also higher (more conservative) than that of the most recent analysis, prepared for the Nuclear Regulatory Commission (NRC, 1985), which proposes a "central estimate" of 190 effects per million man-rem. The choice of one estimate rather than a range also simplifies the analyses presented in Chapters 3, 4, and 5 and thereby improves clarity. Finally, the assumption of a different dose-effect relationship would not change the relative ranking of the nominated sites.

Genetic effects are not included in the analysis because they are strongly and positively correlated with estimates of cancer fatalities. Thus their inclusion would not be expected to alter the site rankings obtained by considering only the fatal effects.

F.1.1 RADIOLOGICAL FATALITIES IN REPOSITORY WORKERS

One of the health-and-safety objectives is to minimize radiological health effects in repository workers. The performance measure for this objective is the number of radiological fatalities incurred by repository workers from exposure at the repository.

Workers at the repository could be exposed to radiation while on the surface or underground. The radiation exposure can come from the radioactive waste or from naturally occurring radionuclides in the rock, during waste-receipt operations, during the preparation of spent fuel for underground emplacement (consolidation and packaging), while transporting the waste underground, during emplacement, and in "caretaker" operations. As explained in Section F.1.3, in estimating the number of workers required for each site, labor requirements were divided into surface and underground categories, and each of these categories was divided into radiation and nonradiation subcategories. The surface radiation category consists of workers assigned to the waste-handling building (i.e., waste receipt and preparation) and the waste shaft (i.e., waste transfer underground). The underground radiation category consists only of the workers involved in waste emplacement. However, as discussed below, all underground workers can be exposed to radiation from the natural radioactivity of the rock.

A key factor for discriminating among the sites is the number of waste-handling operations (i.e., the number of waste packages). The number of waste packages affects the spent-fuel-preparation operations (i.e., packaging), surface transport to the hoist, and underground transport and emplacement. A waste package consists of the waste form, which may be spent fuel or high-level waste, a metal canister for high-level waste, and a metal disposal container; at some sites, an internal canister or an external packing assembly may be included. A repository at any of the sites will handle 16,000 packages of defense high-level waste (equivalent to 8000 MTHM), including a small quantity of commercial high-level-waste from a demonstration project in West Valley, New York. The number of high-level-waste packages therefore does not discriminate among sites. The number of spent-fuel packages, however, varies with the host rock. The number of workers exposed to radiation from surface and underground operations is also important in discriminating among the sites.

While the waste-receipt operations at each site contribute to the total amount of worker exposure, the number of shipping casks received and the receipt operations at each site are comparable at each site and therefore are not considered as discriminators. Other potentially distinguishing factors related to worker exposure during waste-handling operations are too uncertain at this time to be used as discriminating factors. These include the design of the waste packages, the radiological characteristics of the waste packages, the number of workers exposed in each operation, and the time required for each operation. Exposure due to the radiation field created by already emplaced waste is not known at this time but is related directly to the number of waste packages, which in turn depends on the thermal capacity of the host rock, on the spacing of the waste packages, and hence on the partial shielding provided by the host rock itself.

During the construction and operation of the repository, underground workers could be exposed to radiation from naturally occurring radon daughters, thorium daughters, long-lived radionuclides, or gamma radiation from the rock. The amount of exposure received by each worker is directly related to the natural radioactivity of the rock and the ventilation provided the worker. The total exposure is directly proportional to the amount of exposure per worker and the number of underground workers.

The potential hazard to repository workers from the natural radioactivity of the rock is indicated by the concentration of radon daughters that might be expected in the repository atmosphere. The concentration depends on the natural radioactivity of the rock and the ventilation provided. Even for high natural-radioactivity levels, the exposure of workers can be maintained at low levels if good ventilation is provided.

The unit of dose rate for radon in air is the "working level" (W.L.). For reference, the Mine Safety and Health Administration (MSHA) estimates that a worker exposed to 0.4 W.L. for 173 hours per month for a year and a worker exposed to 5 rem per year (the limit allowed for occupational exposure by NRC regulations for reactors) have approximately equivalent risks. In 1984, approximately 97 percent of the radon-daughter-exposure records submitted to the MSHA by the mining industry showed exposures at or below an equivalent of 0.2 W.L. Accordingly, 0.2 W.L. appears to be the worst credible level for this factor. A mine that has a rock with a low radioactivity or very good ventilation operates at concentrations of less than 0.1 W.L. In some mines, such as the Waste Isolation Pilot Plant in New Mexico (a demonstration repository being built in bedded salt for defense transuranic wastes), the dose rate for radon is 0.001 W.L.

With this as background, then, the estimated number of radiological fatalities in repository workers can be calculated from the formula

$$F_{wrad} = [k_{he}][(N_{uc})(t_c)(E_n) + (N_o)(t_o)(E_n) + (N_{rad})(E_o)(t_o)],$$

where

k_{he} = the risk factor = 280 fatalities per million man-rem

N_{uc} = the number of underground-construction workers (full-time equivalents)

t_c = the construction time = 5 years

E_n = the average exposure to radon

N_o = the number of underground-operation workers (full-time equivalents)

t_o = the duration of operations = 26 years

N_{rad} = the number of radiation workers (underground and surface workers)

E_o = the average exposure for radiation workers = 0.5 rem per worker

The work force assumed for each site in the calculations is presented in Table F-1. Because the numbers of workers for the construction and the waste-emplacement periods are much larger than those for the caretaker period and because the activities to be performed during the caretaker period have not been completely defined at present, the latter is ignored in the calculations. The basis for estimating labor requirements and the site characteristics that affect them are discussed in Section F.1.3.

The site impacts are summarized below and are described in the text that follows. The number of fatalities for the base case is given first, followed by estimates for the low-impact and the high-impact cases in parentheses.

Site	Radiological worker fatalities (range)
Deaf Smith	2 (<1-4)
Davis Canyon	2 (<1-4)
Richton Dome	2 (<1-4)
Hanford	9 (<2-17)
Yucca Mountain	4 (<1-9)

Davis Canyon, Deaf Smith, and Richton Dome

For the base case, two radiological fatalities in repository workers are estimated for the salt sites. Since only trace amounts of natural radionuclides are expected in salt, worker exposure to natural radioactivity from the host rock is expected to be minimal. Measurements at the Waste Isolation Pilot Plant in New Mexico show the working level to be 0.001. No ventilation is required for reducing radon concentrations.

Table F-1. Average staffing levels for the repository
(Full-time equivalents[A])

Site and phase[B]	Surface			Underground			Total		
	Radiation	Nonradiation	Subtotal	Radiation	Nonradiation	Subtotal	Radiation	Nonradiation	Total
Davis Canyon									
Construction	0	1165	1165	0	745	745	0	1910	1910
Emplacement	380	450	830	26	387	413	406	837	1243
Caretaker	36	78	114	0	94	94	36	172	208
Backfill	0	79	79	0	222	222	0	301	301
Deaf Smith									
Construction	0	765	765	0	783	783	0	1548	1548
Emplacement	380	450	830	26	434	460	406	884	1290
Caretaker	36	78	114	0	124	124	36	202	238
Backfill	0	79	79	0	243	243	0	322	322
Richton Dome									
Construction	0	785	785	0	668	668	0	1453	1453
Emplacement	380	450	830	26	408	434	406	858	1264
Caretaker	36	78	114	0	102	102	36	180	216
Backfill	0	79	79	0	206	206	0	285	285
Hanford									
Construction	0	552	552	0	933	933	0	1485	1485
Emplacement	487	575	1062	23	573	596	510	1148	1653
Caretaker	35	151	186	0	71	71	35	222	257
Backfill	0	169	169	0	182	182	0	351	351
Yucca Mountain									
Construction	0	398	398	0	439	439	0	837	837
Emplacement	276	596	972	12	273	295	288	869	1157
Caretaker	14	61	75	0	36	36	14	97	111
Backfill	0	0	0	0	0	0	0	0	0

[A] One full-time equivalent equals 2000 man-hours per year.
[B] Assumptions: the construction period is 5 years; the waste-emplacement period is 26 years; the caretaker period is 24 years; the backfill period is 34 years for Hanford and 3 years for all salt sites; backfill is not planned for Yucca Mountain.

The number of underground workers required for the construction and operation of a salt repository is expected to be moderate in comparison with the other sites—an average of about 740 underground workers during construction and about 440 underground workers during the waste-emplacement period. The number of workers exposed to radiation from surface and underground waste-handling operations is expected to be moderate (about 410). The small differences in the numbers of workers among the salt sites (see Table F-1) do not affect the calculations. The number of waste-handling operations is near the minimum that would be required for a 70,000-MTHM repository. The waste to be handled includes about 16,000 containers of spent fuel.

The low-impact estimate for the salt sites is less than one radiological fatality in repository workers. The low-impact case differs from the base case in that the numbers of underground workers and radiation workers are assumed to be about half those of the base case. The number of waste-handling operations is also minimal. While design refinements and waste-handling procedures could be optimized and further reduce the exposures of workers, no substantial reductions in health effects over the nominal case would result.

The high-impact estimate for the salt sites is four radiological fatalities in repository workers. In comparison with the base case, the working level is increased by a factor of 10 to 0.01 W.L., the numbers of underground workers and radiation workers are doubled, and the number of spent-fuel packages is increased by 50 percent.

Hanford

The base-case estimate for the Hanford site is nine radiological fatalities. The basalt rock at Hanford is expected to have a relatively low content of radionuclides (0 to 3 ppm uranium and thorium). The repository is also expected to require a very high ventilation rate to control temperatures, which would limit to low levels the doses received by the underground workers from natural radioactivity in the host rock. As a result, working levels are expected to be less than 0.1. A working level of 0.1 is consistent with reported dose rates in mines in basalt, diorite, and granite. However, most of the exposure from the repository is expected to result from the large number of workers exposed to the low levels of radioactivity in the rock.

The number of underground workers required for construction and operation is expected to be relatively high: an average of about 940 underground workers during construction and an average of 580 during the waste-emplacement period. The number of workers exposed to radiation in surface and underground waste-handling operations is expected to be high (about 510).

Because of the poor thermal capacity of the host rock, the waste package for spent fuel contains smaller quantities of spent fuel than that in the other types of host rock, and this increases the number of waste packages. Thus, the number of waste-handling operations is near the maximum that would be required for a 70,000-MTHM repository. The waste to be handled includes about 35,000 containers of spent fuel.

The low-impact estimate for the Hanford site is two radiological fatalities. The concentration of radon and other natural radionuclides in the repository may be less than that assumed in the base case. The high ventilation rate at Hanford could result in working levels lower than 0.1 W.L. The numbers of underground workers and radiation workers are about half those of the base case. The number of waste-handling operations does not change. While design refinements and waste-handling procedures could be optimized and further reduce the exposures of workers, no substantial reductions in health effects over the base case would result.

The high-impact estimate for the Hanford site is 17 radiological fatalities. This estimate is based on the assumption that the numbers of underground workers and radiation workers projected for the base case are doubled and that the number of spent-fuel packages is increased by 50 percent.

Yucca Mountain

For the Yucca Mountain site, the base-case impact is four radiological fatalities in repository workers. The tuff rock at Yucca Mountain is expected to have a relatively low radioactivity (0 to 3 ppm uranium and thorium). The repository is also expected to require a high ventilation rate to control dust during excavation, and this would also limit to low levels the radiation doses received by the underground workers from the radioactivity in the rock. As a result, working levels are expected to be less than 0.1.

The number of underground workers required for construction and operation is expected to be relatively low: an average of about 440 underground workers during construction and an average of about 290 workers during emplacement. The number of workers exposed to radiation from surface and underground waste-handling operations is expected to be low (about 280).

The number of waste-handling operations is moderate for a 70,000-MTHM repository. The waste to be handled includes about 21,000 containers of spent fuel.

The low-impact estimate for the Yucca Mountain site is one radiological fatality. The concentration of radon and other natural radioactivity in the repository may be less than that assumed in the base case. The high ventilation rate at Yucca Mountain could result in working levels lower than 0.1 W.L. The numbers of underground workers and radiation workers are about half those of the base case. The number of waste-handling operations may be smaller than that of the base case, but not enough to substantially change the impact. While design refinements and waste-handling procedures could be optimized and further reduce the exposures of workers, no substantial reductions in health effects over the base case would result.

The high-impact estimate for the Yucca Mountain site is nine radiological fatalities. This estimate is based on the assumption that the numbers of underground workers and radiation workers projected for the base case are doubled and that the number of spent-fuel packages is increased by 50 percent. The natural-radioactivity level is assumed to be the same as in the base case (0.1 W.L.) because the high ventilation rate makes a higher level unlikely.

F.1.2 RADIOLOGICAL FATALITIES INCURRED BY THE PUBLIC FROM THE REPOSITORY

During the operation of the repository, the public could receive radiation doses from releases (primarily airborne radionuclides) that result from waste handling and preparation at the site, and one of the health-and-safety objectives is to minimize the effects of such exposure. The performance measure for this objective is the number of radiological fatalities incurred by the public from the repository under normal operating conditions. The consequences of accidents at the repository were not evaluated for the reasons explained below.

Generic scenarios for severe accidents that could result in the release of radionuclides during preclosure operations were analyzed for the Final Environmental Impact Statement for the Management of Commercial Radioactive Waste (DOE, 1980) and are referenced in the environmental assessments for the nominated sites (DOE, 1986a-e). As explained in the environmental assessments, site-specific designs for surface and underground facilities are not sufficiently detailed at present for a rigorous evaluation of the radiological consequences of preclosure accidents for any site. However, preliminary evaluations based on these designs were performed. The results of these evaluations, like the results of the generic-scenario analysis, indicate that the radionuclide releases associated with severe waste-handling accidents would be well below regulatory limits and are not expected to vary significantly among sites. Accordingly, radiological accidents were not considered in the preclosure analysis of sites.

Radiation exposures resulting from offsite releases of the natural radioactivity in the mined rock during construction and operation are expected to be insignificant at all of the nominated sites. Therefore the natural radioactivity of the rock is not a discriminator.

The number of radiological fatalities incurred by the population around the repository will depend on the number of exposed people, the duration of their exposure, and the types and concentrations of radionuclides at the point of exposure.

Because of their dependence on meteorological conditions, which are not sufficiently well known for all sites at present, the duration of the exposure and the concentrations of radionuclides at the point of exposure cannot be used as discriminating factors. For example, the concentration of radionuclides in the atmosphere at any given location is highly dependent on the atmospheric-dispersion characteristics of the site. However, data on atmospheric dispersion at some sites are too uncertain to be used as a discriminating factor. In general, the concentrations of radionuclides in the air, and consequently health effects, will decrease as the distance from the release point to the exposed population increases. The types and quantities of radionuclide releases are expected to be comparable at each site and are therefore not considered discriminators.

Several discriminating factors describing the geographical distribution of the population are available for each site. They are the population density of the region (defined here to be a 50-mile radius around a site), distance to highly populated areas of 2500 persons or more, the presence of population centers in the predominant wind direction (i.e., population centers that would be expected to receive more than the average exposure compared with other areas at comparable distances from the repository), and the distance to unrestricted areas (i.e., the nearest possible location where people might live or reside for any significant period of time).

The population density in the region of the site is an important consideration. A population density of fewer than 5 people per square mile in the 50-mile radius around the site would be highly favorable; this is equivalent to about 40,000 people living in a 7850-square-mile area. A population density that is about twice the average population density of the United States (about 76 people per square mile) would be unfavorable; this would be equivalent to about 1.2 million people living in the same 7850 square miles. For comparison, New Jersey has a land area approximately equal to the regional area considered here. With a population of over 7 million people, it has the highest population density of all the States, at about 915 persons per square mile.

In conjunction with the average population density of the region, the presence of highly populated areas in the vicinity of a site must also be considered. A site without any highly populated areas within 50 miles is highly favorable, whereas a site with a highly populated area (or areas) within 5 miles is unfavorable. A "highly populated area" is defined here as a place with a population of 2500 or more, consistent with the definition in the siting guidelines, 10 CFR Part 960 (DOE, 1984).

The presence of population centers in prevailing wind directions was also considered in the performance measure. A location without any population centers within 50 miles in prevailing wind directions is highly desirable. It would be undesirable to have any population centers, particularly any highly populated areas, in the prevailing wind directions within 5 miles of a site.

Existing population distributions were used rather than projected distributions because the projections for the nominated sites are not fully comparable.

Site ownership and control also affect preclosure radiological effects on the public. The greater the distance to potential receptors, the greater the expected dispersion of the airborne radionuclides and the likelihood of reducing exposures. While great distances would be desirable, it would be impractical to control vast land areas, particularly in light of the small offsite releases that are expected from preclosure operations. Location on large Federal reservations would be an obvious advantage. As a reasonable range of distances, a distance of 15 miles from the repository to the fenceline was selected as highly favorable, while a distance of less than 5 miles would be unfavorable. The fenceline distance should be considered in conjunction with the existing population distribution; that is, a site with very few people living within 15 miles of a repository, regardless of the fenceline location, should be considered approximately equal to a site where the repository is 15 miles from an unrestricted area. It is unlikely that there would be major shifts in population centers toward a repository during the period of operation.

In evaluating preclosure radiological safety, it is also necessary to consider various potential exposure pathways that involve the food chain, even though the individual doses received from such pathways during repository operation would be negligible. Among the factors that need to be taken into account is the consumption of food products contaminated by the deposition of radionuclides. The number of health effects experienced by the public will depend on the number of exposed people, the quantity of food consumed, and the types and concentrations of radionuclides in the food. However, little information is available to characterize the specific area of interest for the sites. For example, the food production for the county of the site may be known, but it is not directly comparable with that from other sites because of differences in the sizes of the counties. There are no data showing whether farms are concentrated in the vicinity of the site or whether most farms in the county are remote from the site. However, even without exact information for the sites, it is possible to generally characterize the food-crop production in a region as low, moderate, or high, on the basis of available data, such as the number of acres in the county in farmland and the value of agricultural products sold in the county. A barren area with little or no agricultural production would be ideal. Areas with very high food-crop production would be less desirable.

To provide a mechanism for evaluating each site, the scale shown in Table F-2 was constructed. The worst possible level of impact that might be expected from a nominated site was calculated to be three radiological fatalities. This is the equivalent of each person in the region around a site receiving 0.3 millirem per year for each of the 26 years of waste-emplacement operations, assuming a population density of 152 persons per square mile (a total regional population of about 1.2 million people). In view of the small releases expected from a repository and experience at other nuclear facilities, this estimate is considered to be extremely conservative. For example, the maximally exposed individual at the fenceline of a DOE facility receives less than 0.1 to 0.2 millirem per year. (The maximally exposed individual is a hypothetical person who is assumed to be exposed to a release of radioactivity in such a way that he receives the maximum possible individual dose.)

The model presented in Table F-2 can be used to estimate the performance of the site in terms of the numbers of radiological fatalities incurred by the public from the repository.

The estimated performance of each site is presented below and discussed in the text that follows. The base-case estimate is followed by estimates for the low-impact and the high-impact cases (the range).

Site	Radiological public fatalities (range)
Davis Canyon	0.1 (0.07-0.1)
Deaf Smith	0.5 (0.07-0.5)
Richton Dome	0.7 (0.5-0.7)
Hanford	0.7 (0-0.7)
Yucca Mountain	0.1 (0-0.2)

Davis Canyon

The regional population density at Davis Canyon, at 0.9 people per square mile within 10 miles and 3.8 people per square mile within 50 miles, is very

Table F-2. Qualitative model used to estimate the radiological fatalities incurred by the public from the repository

Approximate number of radiological fatalities	Description of factors in model
0	An extremely low population density (fewer than five persons per square mile) in the general region of the site; great remoteness (about 50 miles) from a highly populated area of 2500 persons; no population centers within 50 miles in predominant wind directions; little or no food-crop production in the region; distance to unrestricted areas more than 15 miles
0.75	A regional population density about half the mean for the continental United States (76 persons per square mile); remoteness (about 35 miles) from a highly populated area of 2500 persons; small or few population centers within 50 miles in predominant wind directions; some food-crop production in region; distance to unrestricted area more than 10 miles
1.5	A regional population density about equal to the mean for the continental United States; a distance of about 20 miles from a highly populated area of 2500 persons; some population centers within 50 miles, but no highly populated areas within 20 miles in predominant wind directions; high food-crop production in the region; distance to unrestricted areas more than 5 miles
2.7	A regional population density about twice the mean for the continental United States; proximity (about 5 to 10 miles) to highly populated areas of 2500 persons; several population centers within 50 miles, but no highly populated areas within 10 miles in predominant wind directions; very high food-crop production in the region
3.0	A regional population density about twice the mean for the continental United States; close proximity (less than 5 miles) to highly populated areas of 2500 persons; several population centers within 50 miles, with highly populated areas within 5 miles in predominant wind directions; very high food-crop production in the region; distance to unrestricted areas less than 5 miles

low. Two highly populated areas are within 50 miles: Moab (5500 people at 33 miles) and Blanding (3000 people at 35 miles). The nearest population center in a predominant wind direction is La Sal, 19 miles away. There are no highly populated areas in the predominant wind directions. The distance to unrestricted areas could be less than 2 miles. The agricultural productivity of the area is low: less than 3 percent of the land in San Juan County, Utah, is being used to raise crops, and the market value of agricultural products sold in the county is about $8 million (less than $2 per acre on the average).

The base-case and the high-impact estimates are the same: less than 0.1 radiological fatality in the public. The population-dose calculations in the environmental assessment for Davis Canyon (DOE, 1986a), assumed here to represent the lowest level of impact, show that the population would receive a total dose of 250 man-rem, which corresponds to about 0.07 radiological fatality.

Deaf Smith

The regional population density at the Deaf Smith site, at 28 people per square mile within 10 miles and 24 people per square mile within 50 miles, is low (about one-third of the national average). The following highly populated areas are within 50 miles of the site: Hereford (16,000 people at 17 miles); Amarillo (150,000 at 30 miles); Canyon (11,000 at 30 miles); Friona (4000 at 34 miles); and Dimitt (5000 at 36 miles). The nearest population centers in predominant wind directions are Masterson and Excell at 50 miles from the site. There are no highly populated areas in predominant wind directions. The distance to unrestricted areas could be less than 0.5 mile. The agricultural productivity of the area is relatively high: about 58 percent of the land in Deaf Smith County, Texas, is being used to raise crops, and the market value of the agricultural products sold in the county is about $565 million (about $600 per acre on the average).

The base-case and the high-impact estimates of health effects in the public are the same; 0.5 radiological fatality, which is equivalent to an average dose of 0.35 millirem per year to each person in the region. The population-dose calculations in the environmental assessment for the Deaf Smith site (DOE, 1986b) show an average individual dose of about 0.07 millirem per year (a population dose of 390 man-rem, or about 0.1 radiological fatality). This is considered to be the lowest level of impact.

Richton Dome

The regional population density at the Richton Dome site, at 16 people per square mile within 10 miles and 40 people per square mile within 50 miles, is low. The following highly populated areas are within 50 miles: the Petal-and-Hattiesburg area (50,000 people at 16 miles), Palmer's Crossing (2800 at 18 miles), Ellisville (4700 at 20 miles), Laurel (22,000 at 22 miles); Waynesboro (4400 at 27 miles), and Wiggins (3200 at 33 miles). There are no population centers in predominant wind directions within 50 miles. The distance to unrestricted areas could be less than 0.5 mile. The agricultural productivity of the area is low: about 7 percent of the land in Perry County, Mississippi, is being used to raise crops, and the market value of agricultural products sold in the county is about $7 million (about $17 per acre on the average).

The base-case and the high-impact estimates of health effects in the public are the same: 0.7 radiological fatality, which is equivalent to an average dose of 0.3 millirem per year to each person in the region. The population-dose calculations in the environmental assessment for the Richton Dome site (DOE, 1986c) show an average individual dose of about 0.2 millirem per year (a population dose of 1900 man-rem, or 0.5 radiological fatality). This is considered to be the lowest level of impact.

Hanford

The regional population density at Hanford, at 0.4 people per square mile within 10 miles and 43 people per square mile within 50 miles, is low. The large restricted area of the DOE's Hanford reservation provides the obvious advantage of separating potential releases and the public by a large distance. The following highly populated areas are within 50 miles of the site in approximate order by distance: Sunnyside (9300 people at 15 miles); West Richland (3000 people); Richland (34,000 people); Prosser (4100 people); Pasco (19,000 people); Kennewick (35,000 people); Othello (4500 people); Grandview (5700 people); Toppenish (6500 people); Wapato (3300 people); Union Gap (3200 people); Yakima (50,000 people at 40 miles); Selah (4400 people); Moses Lake (11,000 people); Quinex (3500 people); and Umatilla (3200 people at 50 miles). The nearest population centers, which are also highly populated areas, in predominant wind directions are Richland, Pasco, and Kennewick, about 22 to 28 miles away. Because of the large size of the Hanford reservation, the distance to unrestricted areas is about 8 miles. The agricultural productivity of the area is moderate: about 40 percent of the land in Benton County, Washington, is being used to raise crops, and the market value of agricultural products sold in the county is about $140 million (about $130 per acre on the average). No agriculture is permitted on the Hanford reservation; this creates a significant buffer zone in regard to limiting the food-chain exposure pathway.

The base-case and the high-impact estimates of health effects in the public are the same: 0.7 fatality, which is equivalent to an average dose of 0.3 millirem per year to each person in the region. The environmental assessment for Hanford (DOE, 1986d) does not present regional population doses, but it estimates that an individual residing 16 miles from the repository would receive a dose of 0.001 millirem per year. Applying this conservatively to the overall population as an average would result in a population dose of 9 man-rem, or nearly zero health effects for the region.

Yucca Mountain

The regional population density at Yucca Mountain, at no people within 10 miles and 2.5 people per square mile within 50 miles, is ideal. There are no highly populated areas within 50 miles, nor are there any population centers in predominant wind directions within 50 miles. The distance to unrestricted areas is 5 miles or more. The agricultural productivity of the area is very low: about 0.2 percent of the land in Nye County, Nevada, is being used to raise crops, and the market value of agricultural products sold in the county is about $5 million (about $0.40 per acre on the average).

The base-case and the high-impact estimates of health effects in the public are the same: less than 0.1 radiological fatality. While regional population doses were not presented in the environmental assessment for Yucca Mountain (DOE, 1986e), the "bounding" dose estimated for the maximally exposed individual is 0.2 millirem per year. Applying this conservatively to the overall population as an average would result in a population dose of about 100 man-rem, or nearly zero health effects for the region.

F.1.3 NONRADIOLOGICAL FATALITIES IN REPOSITORY WORKERS

One of the eight health-and-safety objectives is minimizing the nonradiological effects experienced by repository workers, and the performance measure is the number of nonradiological fatalities attributable to the repository.

The cause of nonradiological fatalities in repository workers is assumed to be accidents during construction and operation. For completeness, the potential effects of air pollutants at the site were also examined, using data reported in the environmental assessment for the Hanford site (DOE, 1986d). (The environmental assessments for the other sites did not examine the onsite impacts of air pollution.) The calculations showed that the onsite concentrations of sulfur dioxide and nitrogen dioxide would be considerably lower than the limits specified by the national ambient air quality standards. The concentration of inhalable particulates (IP), assuming that inhalable particulates constitute 50 percent of the total suspended particulates, might exceed the proposed IP standard (see Section F.1.4), but it would not pose a hazard to health. Thus, no deaths are expected to result in the Hanford workers from the air quality at the site, and this conclusion is applicable to the other sites as well.

The number of total nonradiological fatalities, F_T, is estimated by the following formula:

$$F_T = F_S + F_{UG}, \qquad \text{(F-1)}$$

where F_S is the estimated number of fatalities from surface-facility construction and operation and F_{UG} is the estimated number of fatalities from underground-facility construction and operation. The quantities F_S and F_{UG} are defined as follows:

$$F_S = K_S \times \text{man-hours (surface)}$$

and

$$F_{UG} = K_{UG} \times \text{man-hours (underground)},$$

with K_S and K_{UG} being the surface-accident and the underground-accident rate per million man-hours, respectively.

A fatality rate of 0.17 fatality per million man-hours of construction for the surface facilities and 0.55 fatality per million man-hours for underground mining was used. The surface-fatality rate is based on current statistics compiled by the National Safety Council for similar industrial operations and is the same as the rate used in the generic environmental impact statement (DOE, 1980, p. 5.56). The underground-fatality rate is a historical 5-year average (1978 through 1982) of fatalities for both nonmetal and metal underground mines (other than coal). This rate is assumed to be representative of a repository because some elements of underground repository construction and operation will be similar to both classes of underground mining. For example, long drifting is likely to use mechanized mining operations of one kind or another, but the drilling and preparation of individual waste-emplacement holes and drifts is likely to require techniques that are more labor-intensive. As a result, underground repository operations have little precedent in the mining of any single commodity, and it seems reasonable to include the injury experience from both metal and nonmetal mining operations. The assumed rate for underground fatalities is very close to the rate cited in the generic environmental impact statement.

It is further assumed that the accident rate will be constant. This assumption is reasonable (though not intuitively obvious) because the accident rates for both metal and nonmetal mines encompass the different geologic environments of the sites under consideration (hard rock and salt) and because the rates are not very different (0.57 for metal mines and 0.52 for nonmetal mines). Furthermore, additional measures would be taken at sites where safety problems can be expected (for example, at Deaf Smith closer spacing for rock bolting would be necessary than at Davis Canyon), and hence the accident rate is likely to be roughly the same at all sites.

The total number of man-hours for construction and operation is derived from the most recent repository-cost estimates and is presented in Table F-3.

Table F-3. Estimated labor requirements for repository construction and operation (Millions of man-hours)

Site	Surface facilities			Underground facilities		
	Construction	Operation	Total	Construction	Operation	Total
Davis Canyon	11.7	46.2	57.9	7.4	23.4	30.8
Deaf Smith	7.7	46.2	53.9	7.8	27.4	35.25
Hanford	5.5	72.0	77.5	9.3	45.0	54.3
Richton	7.9	46.2	54.1	6.7	24.7	31.4
Yucca Mountain	4.0	47.1	51.1	4.4	13.1	17.5

Substituting the data from Table F-3 and the previously mentioned fatality rates into Equation F-1 yields the following estimates of nonradiological fatalities in repository workers for the five sites (ranges are given in parentheses:

Site	Nonradiological worker fatalities (range)
Davis Canyon	27 (17-36)
Deaf Smith	29 (19-39)
Richton Dome	27 (17-36)
Hanford	43 (28-58)
Yucca Mountain	18 (12-24)

The ranges were calculated by assuming a 35-percent uncertainty (plus or minus) about the labor requirements.

The labor requirements were developed for the 1986 analysis of the total-system life-cycle costs (Weston, 1986), which was performed for assessing the adequacy of the fee paid into the Nuclear Waste Fund. These requirements are based on site-specific designs for a two-phase repository. The construction period covers the surface facilities, the shafts or ramps, and a limited amount of underground development to permit the repository to start receiving waste in 1998. The remaining underground development is included in the operation period. The operation period covers waste receipt, preparation (consolidation and packaging), and emplacement; underground development and maintenance; administration and support functions; the caretaker phase necessary to meet the NRC's requirement for 50-year waste retrievability; and backfilling.

The labor requirements were separated into surface and underground categories to provide information about the location of repository workers. In addition, each of these categories was divided into radiation and non-radiation subcategories to estimate the portion of the labor force working in waste-handling operations during operation (no radioactive wastes are present at the site during construction). The surface-labor category includes the waste-handling buildings, the site, offsite improvements, support facilities, and utilities. The workers assigned to the waste-handling building and the waste shaft comprise the surface radiation category. All other workers are assigned to the nonradiation category. The underground labor category includes shafts and ramps, underground development (the excavation and maintenance of all rooms and corridors), waste emplacement, underground support services, and backfilling and sealing. Waste emplacement is the only underground function assigned to the radiation category. The site characteristics that affect the labor requirements are discussed below.

Davis Canyon

The total labor requirements for the Davis Canyon site are nearly midway between the highest and the lowest estimates (i.e., the requirements for the Hanford and the Yucca Mountain sites, respectively), and they are the highest of the three salt sites. The surface-construction labor requirements and the total construction requirements are the highest of all sites considered.

Surface-facility construction and operation. The total surface-labor requirements for Davis Canyon are higher than those for all other sites because of the construction needed for the access corridors.

The Davis Canyon site has higher surface-labor requirements for construction than any other site. The labor requirements are higher because of the following key factors:

1. The site-access labor requirements for Davis Canyon are the highest of all sites; they are attributable mainly to the bridge and tunnel construction required for the railroad and the access road.

2. The waste-handling facilities are larger than those for Hanford and Yucca Mountain (they are the same for all salt sites).

3. The waste package consists of spent fuel consolidated in metal canisters, which are encapsulated in thick-walled carbon-steel disposal containers.

4. Because of the assumed gassy underground conditions, the repository-ventilation facilities (shaft buildings) are significantly larger than those for Hanford and Yucca Mountain. (These facilities are the same for all salt sites.)

The surface-labor requirements for operation are nearly identical (within 0.1 percent) for the salt sites and lower than those for Yucca Mountain (2 percent) and Hanford (55 percent). The key discriminators that account for these differences are the number and the type of waste packages, and the length of the backfill phase. Like the other salt sites, Davis Canyon prepares the smallest number of waste packages, but the use of thick-walled containers with internal canisters adds to the number of waste-preparation steps. The number of waste-handling and support workers for all the salt sites is very comparable to that of Yucca Mountain, but considerably lower than that of Hanford. Like the other salt sites, Davis Canyon requires more surface radiation workers than does Yucca Mountain because more waste-preparation steps are required. The number of these workers is lower than that for Hanford, which prepares nearly twice as many waste packages. The backfill phase, which requires administrative and support workers, is 3 years for all salt sites, as opposed to a 34-year phase for Hanford. (No backfill is planned for Yucca Mountain.)

<u>Underground-facility construction and operation</u>. The underground-labor requirements of the salt sites are about midway between those for Hanford (highest) and Yucca Mountain (lowest). Davis Canyon has lower underground-labor requirements than do the other salt sites. However, all salt sites require the same number of underground radiation workers (waste-emplacement workers).

The Davis Canyon requirements for underground-construction labor are between those for Deaf Smith (highest) and Richton Dome (lowest). These requirements are determined by the depth of the shafts, requirements for shaft lining, and the rock conditions of the site. Like the other salt sites, Davis Canyon requires five shafts with hydrostatic linings. However, Davis Canyon does not require ground freezing, while Deaf Smith and Richton Dome do, and the rock conditions at Davis Canyon require less artificial support than those at Deaf Smith. On the other hand, the shafts at Davis Canyon are deeper than those at the other salt sites.

In regard to the requirements for underground-operation labor, the salt sites differ in some respects from Hanford and Yucca Mountain. The shafts at the salt sites are significantly deeper than those at Yucca Mountain but less deep than those at Hanford. Excavation at the salt sites has the highest productivity because mechanized mining, rather than conventional techniques, is used. However, the total quantity of rock mined is nearly 300 percent higher than that at Hanford and over 50 percent higher than that at Yucca Mountain. The large increase is attributed to the layout required by the assumed gassy mine conditions. Thus, the high productivity is offset by the size of the excavation.

For the operation phase, the underground-labor requirements for Davis Canyon show the same trends as construction, but the shaft-related discriminators are not applicable. The salt sites are distinguished from the other sites by the following:

1. Unlike Hanford and Yucca Mountain, the salt sites require periodic reexcavation of open drifts to prevent closure by salt creep. (Davis Canyon is assumed to have the lowest rate of creep of all salt sites.)

2. During the waste-emplacement period, the salt sites require continuous backfilling of rooms and corridors as opposed to keeping the entire repository open. As a result, some rock-hoisting labor is eliminated, but the total quantity of rock hoisted is nearly the same as that for the other sites. At the salt sites, the mined rock not needed for backfill must be shipped off the site to prevent soil contamination with salt.

3. The salt sites require the smallest number of waste-emplacement holes because fewer waste packages are prepared.

Deaf Smith

The total labor requirements for the Deaf Smith site are between those for Hanford (highest) and Yucca Mountain (lowest). This observation pertains to both surface and underground labor.

Surface-facility construction and operation. The total surface-labor requirements for Deaf Smith are lower than those for Hanford but higher than those for Yucca Mountain.

The salt sites have the highest surface-labor requirements, and of the salt sites, Deaf Smith has the lowest surface-labor requirements, although Richton Dome is very similar. The requirements exceed those of Hanford and Yucca Mountain because, as already mentioned, the salt sites require larger wastehandling facilities and prepare waste packages with internal canisters encapsulated into thick-walled carbon-steel disposal containers. Furthermore, the repository-ventilation facilities (shaft buildings) are significantly larger for the salt sites because of the assumed gassy mine conditions.

The site-preparation and site-access requirements for Deaf Smith are lower than those for the other salt sites and Yucca Mountain, but higher than the requirements for Hanford.

The surface-labor requirements for operation are nearly identical (within 0.1 percent) for all of the salt sites and lower than those for the nonsalt sites (the Yucca Mountain requirements are only 2 percent higher, while the Hanford requirements are 55 percent higher). The key discriminators are described in the discussion of the Davis Canyon site.

Underground-facility construction and operation. Deaf Smith has the highest underground-labor requirements of all the salt sites, though Richton Dome is only 13 percent lower. All of the salt sites require the same number of waste-emplacement workers.

The Deaf Smith requirements for underground-construction labor are the second highest (next to Hanford) for the following reasons:

1. Five shafts must be sunk through water-bearing rock formations. This requires ground freezing and hydrostatic linings.

2. The Deaf Smith shafts are deeper than those at Richton Dome (but not as deep as those at Davis Canyon). (The shafts at all the salt sites are significantly deeper than those at Yucca Mountain).

3. Because of the assumed gassy mine conditions, the total quantity of rock mined is nearly 300 percent higher than that at Hanford and over 50 percent higher than that at Yucca Mountain, though this is offset by the high productivity of excavation at the salt sites (see the discussion of the Davis Canyon site).

4. The rock conditions at Deaf Smith require more rock bolting and roof support than do those at the other salt sites.

For operation, the underground-labor requirements for Deaf Smith show the same trends as construction, except that the shaft-related discriminators are not applicable and the discriminators discussed for Davis Canyon (requirements for the periodic reexcavation of open drifts, continuous backfilling of rooms and corridors, and the smallest number of waste-emplacement boreholes) are applicable. At Deaf Smith, the rate of salt creep is more than twice the rate at Richton Dome and thrice the rate at Davis Canyon.

Richton Dome

In total labor requirements, the Richton Dome site is between Hanford and Yucca Mountain. This observation pertains to both surface- and underground-labor requirements. It has the lowest labor requirements of the three salt sites.

Surface-facility construction and operation. The total surface-labor requirements are lower than those for Davis Canyon and Hanford, higher than those for Yucca Mountain, and similar to those for Deaf Smith.

The surface-labor requirements for construction are lower than those for Davis Canyon, slightly higher than those for Deaf Smith (because more site preparation is needed), and higher than those for Hanford and Yucca Mountain, as explained previously.

Underground-facility construction and operation. Richton Dome has the lowest underground-labor requirements of all the salt sites. All salt sites have the same number of waste-emplacement workers.

The underground-labor requirements for construction are the second lowest (next to Yucca Mountain) of all sites and the lowest of the salt sites because the shafts at Richton Dome are deeper than those at Yucca Mountain but less deep than those at Hanford and those at the other salt sites, and the rock conditions at Richton Dome require less rock bolting and roof support than those at Deaf Smith and about the same as those at Davis Canyon.

For operation, the underground-labor requirements for Richton Dome show the same trends as construction except that the shaft-related discriminators are not applicable. Like the other salt sites, Richton Dome requires periodic reexcavation to counteract salt creep, but the rate of salt creep at Richton is less than half the rate assumed for Deaf Smith and nearly twice the rate for Davis Canyon. The requirements for backfilling and the number of waste-emplacement holes are also like those of the other salt sites.

Hanford site

The Hanford site has the highest total labor requirements. Its requirement for construction labor is lower than that of Davis Canyon and Deaf Smith, but the operating labor is the highest of all sites considered.

Surface-facility construction and operation. The surface-labor requirements for Hanford are the second highest (next to Davis Canyon). The requirements for construction are next to the lowest (Yucca Mountain), but the operation requirements are the highest of all sites.

The surface-labor requirements for construction are low because Hanford requires less site preparation and site-access construction than do the other sites.

The high surface-labor requirements for operation are attributable to the following:

1. The need to handle the largest number of waste packages and to add a packing assembly (for a bentonite-and-basalt packing material) around the waste disposal container. This results in a higher requirement for surface radiation labor than at any other site.

2. The backfill period (34 years) is much longer than that for the salt sites (3 years). (No backfill is planned for the Yucca Mountain site.)

3. Of all the sites considered, Hanford has the highest surface-labor requirements for the caretaker phase because of the need to maintain open the shafts and underground areas. The Hanford repository has the greatest number of shafts and requires significant support services (ventilation and water control) to keep the entire underground area accessible during the caretaker phase. (The salt repositories keep only the main corridors open.)

Underground-facility construction and operation. Of all the sites considered, Hanford has the highest underground-labor requirements for both construction and operation. The construction-labor requirements are high because Hanford has the greatest number of shafts, and the shafts are the deepest. Furthermore, the productivity of excavation is lower at Hanford than at the other sites (about 33 and 38 percent of the productivity for the salt sites and Yucca Mountain, respectively). Productivity depends on the host-rock conditions (stress, temperature, hardness, etc.), ground-water conditions, and mining methods.

The high underground-labor requirements for operation are attributable to the long backfilling period (34 years) and the requirement for more waste-emplacement boreholes, which is due to the greater number of waste packages.

Yucca Mountain

The Yucca Mountain site has the lowest total labor requirements and the lowest construction- and operating-labor requirements of all sites considered.

Surface-facility construction and operation. The total surface-labor requirements are the lowest of all the sites considered because of low construction-labor requirements. The labor requirements for operation are slightly greater than those of the salt sites.

The low construction-labor requirements are attributed to a surface-facility design that is quite different from that for the other sites:

1. The size of the waste-handling facilities is about 60 percent of that for Hanford and the salt sites.

2. The waste package for spent fuel uses thin-walled stainless-steel disposal containers and no internal canisters.

3. The repository-ventilation facilities (shaft buildings) are much smaller than those of the other sites (about 17 percent of those at Hanford and only 5 percent of those at the salt sites) because of favorable underground conditions.

At Yucca Mountain, the surface-labor requirements for operation are lower than those for the Hanford site but slightly higher than those for the salt sites, partly because the total surface-labor requirements follow the trend of waste-package quantities (salt sites lowest and Hanford highest).

Other pertinent factors include the following:

1. The waste-handling building requires less labor for waste preparation (fewer radiation workers). This reduction is due to the use of thin-walled waste containers.

2. Less caretaker labor is needed than at Hanford and the salt sites, because a separate diagnostic facility is used for performance confirmation. The other sites must maintain a waste-handling building since no separate facility is included in their designs.

3. In comparison with Hanford, a considerable labor reduction results from eliminating the support and administrative staff needed for the backfill phase, which is not planned for Yucca Mountain.

Underground-facility construction and operation. The underground-labor requirements for both construction and operation at Yucca Mountain are significantly lower than those for the other sites considered.

The underground-construction labor requirements are about 50 percent to 60 percent of those for Hanford and the salt sites, respectively. These differences are attributable to--

1. Shaft depths, which are 30 to 40 percent of the depths for Hanford and the salt sites, respectively.

2. The use of ramps instead of two shafts for access underground.

3. Absence of water-bearing formations in the strata through which shafts are sunk and hence no need for hydrostatic linings.

4. A repository horizon located above the water table.

5. The absence of gassy mine conditions and an excavation volume that is 50 percent smaller than that of the salt sites.

6. Favorable rock stability, ground-water quantities, and working temperatures (without air conditioning), which allow the excavation productivity to be 260 percent higher than at Hanford (but 13 percent lower than at the salt sites).

The underground-labor requirements for operation are also much lower than those for the other sites. In addition to the discriminators discussed for construction, there are two other key discriminators. First, no backfilling of underground rooms and corridors is planned. In comparison with all the other sites, this represents a very significant labor reduction. Second, significantly less underground radiation labor is needed because the Yucca Mountain design uses a single waste transporter to move waste underground (via a ramp rather than a shaft) and to emplace it. This eliminates some waste handling, such as transfer on and off shaft conveyances.

F.1.4 NONRADIOLOGICAL FATALITIES INCURRED BY THE PUBLIC FROM THE REPOSITORY

To minimize adverse nonradiological effects on the public is one of the health-and-safety objectives, and its performance measure is the number of nonradiological fatalities incurred by the public from the repository. The mechanism for such effects was postulated to be exposure to the air pollutants generated during repository construction and operation. Air-pollution impacts on the public were examined mainly for the sake of completeness because significant adverse effects were not expected.

Equipment used during the construction and operation of the repository will generate various air pollutants--namely, particulates, oxides of nitrogen (NO_x), sulfur dioxide (SO_2), and carbon monoxide (CO). At high dosages these air pollutants may cause illness and even death. In remote rural areas, air pollution may exert an effect on aesthetics. This effect is treated in Section F.2.1.

Limits on the ambient ground-level concentrations of these pollutants are set by the Environmental Protection Agency (EPA) in the national ambient air quality standards (NAAQS). National primary standards for ambient air quality define the levels of air quality that are necessary, with an adequate margin of safety, to protect public health. National secondary standards define the air-quality levels necessary to protect the public from any known or expected adverse effects of a pollutant. Ambient-air-quality levels below the NAAQS would be expected to result in no additional deaths.

The EPA is currently in the process of modifying the standard for the 24-hour and annual concentrations of particulates. The current standard is for total suspended particulates (TSP) and covers particles of all sizes. The future standard will cover only inhalable particulates (IP), which are smaller than about 15 micrometers in diameter. The rationale for this change is that only the smaller particles are responsible for respiratory distress, primarily in sensitive persons with preexisting respiratory problems, such as asthma. The future annual IP standard is expected to be in the range from 50 to 65 micrograms per cubic meter.

The estimates of annual air-quality impacts that are presented in the environmental assessments for the nominated sites (DOE, 1986a-e) were examined to determine the peak offsite concentrations of air pollutants. The concentrations of inhalable particulates were estimated by assuming that the IP fraction represented no more than 50 percent of the estimated total suspended particulates. This assumption is probably somewhat conservative because the IP fraction in fugitive dust is typically less 50 percent, though it could approach 50 percent at certain locations.

As discussed below, the maximum predicted offsite concentrations of all pollutants are expected to be below the respective national standards. Therefore, no deaths are expected in the general public from air pollution at any of the five sites.

Davis Canyon

The maximum offsite annual concentration of nitrogen dioxide, occurring during repository operation, is predicted to be 22 micrograms per cubic meter. The maximum offsite concentration of total suspended particulates is predicted to be 24 micrograms per cubic meter, occurring during repository construction, and thus the IP levels should be well within the future standard. The concentrations of other pollutants will also be easily within the applicable standards.

Deaf Smith

The maximum offsite annual concentration of nitrogen dioxide, occurring during repository operation, is predicted to be 22 micrograms per cubic meter. The maximum offsite concentration of total suspended particulates is predicted to be 69 micrograms per cubic meter, occurring during site characterization, and thus the IP levels should be within the future standard. The concentrations of other pollutants will also be easily within the applicable standards.

Richton Dome

The maximum offsite annual concentration of nitrogen dioxide, occurring during repository operation, is predicted to be 24 micrograms per cubic meter. The estimated maximum IP level, 21 micrograms per cubic meter, would occur during site characterization; this estimate is based on the expected concentration of total suspended particulates (42 micrograms per cubic meter). The levels of other pollutants are expected to be small in comparison with the applicable standards.

Hanford

The maximum offsite annual concentration of nitrogen dioxide, occurring during repository operation, is predicted to be well within the standard. The offsite levels of inhalable particulates are predicted to be within the future standard. The concentrations of other pollutants are expected to be small in comparison with the applicable standards.

Yucca Mountain

Annual offsite concentrations of nitrogen dioxide and total suspended particulates were not estimated in the environmental assessment. However, the estimated 24-hour concentrations indicate that the annual concentrations would be within the applicable standards.

F.1.5 RADIOLOGICAL FATALITIES INCURRED BY THE PUBLIC FROM WASTE TRANSPORTATION

Four objectives related to health and safety were defined for waste transportation. Two of them are concerned with minimizing radiological effects on waste-transportation workers and the public, and two are concerned with nonradiological effects on workers and the public. This section discusses the performance predicted for each site on the objective of minimizing radiological effects on the public.

Performance against this objective is measured by the predicted number of radiological fatalities incurred by the public from waste transportation. The approach to the calculations of risk is only outlined here, as risk analyses for transportation operations have been well documented elsewhere.

The number of fatalities attributable to waste transportation is calculated by the RADTRAN code, which has been used by the Nuclear Regulatory Commission in evaluating the risk of transporting radioactive materials (NRC, 1977 and 1983) and is the basis of other risk-assessment tools (Finley et al., 1980; Ericsson and Elert, 1983).

Four factors are needed to assess the risk from waste-transportation operations: unit-risk factors, shipment distances, fractions of travel in various population zones, and the number of shipments.

Unit-risk factors represent the risk per unit distance in a defined population zone. The factors used to assess the impacts of shipments that originate at reactors and the sources of high-level waste are given in Table F-4. Factors are given for truck and rail shipments through each type of population zone under both normal and accident conditions. The normal risk is divided into worker and public categories. The accident risk is not divided because potential exposures for each category are similar, and the population density used in the calculations can be considered to include both categories.

Shipment distances to each site are given in Tables F-5 and F-6 for selected reactors in different regions of the United States and sources of high-level waste, respectively. A summary of total shipment distances is given in Table F-7 for each transportation scenario.

Population zones are defined as follows: rural, 6 persons per square kilometer; suburban, 719 persons per square kilometer; and urban, 3861 persons per square kilometer. The fractions of travel through the various population zones are given in Tables F-8 and F-9 for the selected reactors and the high-level-waste sites, respectively. These fractions of travel were determined by analyzing a representative route from each source. Further details and data for all other reactors are presented by Cashwell et al. (1985).

The numbers of shipments from each reactor to each site are given in Table F-10.

The uncertainty associated with the results is thought to have two components: one related to the effect of the second repository and the other to the analytical models and data. The reader is referred to Section A.11 of Appendix A of the environmental assessments (DOE, 1986a-e) for a discussion of the analysis that was performed to assess the potential effect of the second repository on the results calculated for the first repository. That analysis showed that the uncertainty associated with the second repository is +40 and -46 percent. This means that, under the best circumstances, the second repository could reduce shipment distances by as much as 46 percent. Conversely, under the worst circumstances, shipment distances could increase by as much as 40 percent. In addition, the uncertainty inherent in the models and data is estimated to be +0 and -100 percent. From this it is obvious that the minimum number of radiological fatalities in the public from transportation to all sites will be 0. In other words, it is believed that, because of the conservative nature of the models and data, it is possible that the expected values could be reduced by as much as 100 percent.

In assessing the sites, both normal and accident conditions for each of two modes of transportation (truck and rail) were considered. The analyses contained in Appendix A of the environmental assessments (DOE, 1986a-e) present results for all-truck and all-rail transportation because these represent bounding cases for risk. However, to more closely represent the actual conditions at the time shipments are made, a rail fraction of 70 percent was assumed over the lifetime of the repository. Although this fraction cannot be predicted with complete certainty, it is assumed to be reasonable and representative. It is obtained by assuming that, at the time of shipment, the reactors that are capable of shipping by rail will do so, and the weight of spent fuel from those reactors will be about 70 percent of the total. The remaining 30 percent will be shipped by truck.

Table F-4. Radiological risk factors for shipments from waste sources to the repository[a]

Mode	Zone	Hazard group[c]	Spent fuel[b]	High-level waste[b] Defense	Commercial
Truck	Rural	Normal worker fatalities	4.70E-09[d]	4.14E-09	4.14E-09
Truck	Rural	Normal public fatalities	2.84E-08	2.54E-08	2.54E-08
Truck	Rural	Accidental public fatalities	3.10E-13	2.56E-13	1.79E-13
Truck	Suburban	Normal worker fatalities	1.03E-08	9.10E-09	9.10E-09
Truck	Suburban	Normal public fatalities	4.36E-08	3.92E-08	3.92E-08
Truck	Suburban	Accidental public fatalities	7.46E-10	1.08E-10	7.60E-11
Truck	Urban	Normal worker fatalities	1.72E-08	1.52E-08	1.52E-08
Truck	Urban	Normal public fatalities	5.96E-08	5.36E-08	5.36E-08
Truck	Urban	Accidental public fatalities	1.22E-09	2.16E-10	1.52E-10
Rail	Rural	Normal worker fatalities	2.14E-09	2.04E-09	1.03E-09
Rail	Rural	Normal public fatalities	1.15E-09	1.03E-09	1.03E-09
Rail	Rural	Accidental public fatalities	1.34E-12	5.56E-13	5.40E-13
Rail	Suburban	Normal worker fatalities	2.14E-09	2.04E-09	2.04E-09
Rail	Suburban	Normal public fatalities	7.70E-09	6.90E-09	6.90E-09
Rail	Suburban	Accidental public fatalities	2.78E-09	2.72E-10	2.64E-10
Rail	Urban	Normal worker fatalities	2.14E-09	2.04E-09	2.04E-09
Rail	Urban	Normal public fatalities	2.58E-09	2.32E-09	2.32E-09
Rail	Urban	Accidental public fatalities	6.72E-09	5.08E-09	4.92E-09

[a] Risk factors given per kilometer. To convert factors to risk per mile multiply by 1.609. Risk estimates based on the assumption that a population dose of 1 man-rem leads to 0.0002 radiological fatality plus firstand second-generation genetic effects.

[b] Unit risk factors for general-commerce transportation by truck or rail; units are per kilometer for truck and per railcar-kilometer for rail.

[c] "Normal" and "accidental" fatalities are the fatalities incurred from transportation under normal conditions and under accident conditions, respectively.

[d] Computer notation is used in this table; thus, 4.70E-09 = 4.70×10^{-9}.

Table F-5. Distance per shipment from selected[a] reactors

Reactor	Distance (miles) Richton Dome	Deaf Smith	Davis Canyon	Yucca Mountain	Hanford
Maine Yankee (Maine)					
Truck	1570	2150	2570	3040	3107
Rail	1920	2180	2750	3270	3150
Crystal River (Florida)					
Truck	579	1670	2310	2600	2990
Rail	571	1699	2450	3000	3210
Quad-Cities (Illinois)					
Truck	959	1040	1300	1780	1910
Rail	1080	937	1480	2000	1980
Palo Verde (Arizona)					
Truck	1908	789	509	606	1550
Rail	1950	933	1790	652	1690
Trojan (Oregon)					
Truck	2780	1850	1190	1330	302
Rail	2919	2210	1250	1460	301

[a]These reactors were chosen as representative of regions throughout the country.

Table F-6. Distance per shipment from sources of high-level waste

Source	Distance (miles)				
	Richton Dome	Deaf Smith	Davis Canyon	Yucca Mountain	Hanford
Hanford					
Truck	2610	1660	1010	1150	NA
Rail	2670	1730	1070	1288	NA
Idaho National Engineering Laboratory					
Truck	2160	1210	604	740	610
Rail	2110	1200	555	763	696
Savannah River Plant					
Truck	568	1420	2060	2350	2740
Rail	644	1520	2200	2750	2890
West Valley[a]					
Truck	1160	1580	2000	2750	2550
Rail	1450	1690	2100	2860	2660

[a] Commercial high-level waste from the West Valley Demonstration Project.

Table F-7. Total cask miles
(Millions of one-way miles)

Mode and waste type	Cask miles				
	Richton Dome	Deaf Smith	Davis Canyon	Yucca Mountain	Hanford
100% Truck					
Spent fuel	67.4	94.4	115.1	141.8	149.7
High-level waste					
Defense	28.0	26.0	28.0	33.0	35.0
Commercial	1.0	1.0	2.0	2.0	2.0
100% Rail					
Spent fuel	11.0	15.4	18.8	23.2	24.6
High-level waste					
Defense	6.5	6.1	6.5	7.6	8.4
Commercial	0.2	0.2	0.2	0.3	0.3
Totals					
Truck from origin	186.7	96.4	121.4	145.1	176.8
Rail from origin	17.7	21.7	25.5	31.1	33.3

Table F-8. Fraction of travel in population zones from selected reactors to nominated sites

Reactor	Richton Dome Truck	Richton Dome Rail	Deaf Smith Truck	Deaf Smith Rail	Davis Canyon Truck	Davis Canyon Rail	Yucca Mt. Truck	Yucca Mt. Rail	Hanford Truck	Hanford Rail
Maine Yankee (Maine)										
Urban	0.01	0.02	0.01	0.03	0.01	0.01	0.01	0.01	0.01	0.02
Suburban	0.43	0.48	0.35	0.34	0.28	0.23	0.26	0.21	0.26	0.27
Rural	0.57	0.50	0.64	0.63	0.71	0.76	0.74	0.78	0.73	0.71
Crystal River (Florida)										
Urban	0	0.01	0.01	0.02	0	0.01	0.01	0.01	0.01	0.01
Suburban	0.19	0.18	0.23	0.24	0.22	0.17	0.17	0.16	0.19	0.18
Rural	0.81	0.81	0.77	0.74	0.78	0.82	0.82	0.83	0.80	0.82
Quad-Cities (Illinois)										
Urban	0	0.02	0	0	0.01	0.01	0	0.01	0	0.01
Suburban	0.19	0.24	0.18	0.13	0.11	0.08	0.12	0.09	0.10	0.12
Rural	0.81	0.74	0.82	0.86	0.88	0.91	0.88	0.90	0.90	0.87
Palo Verde (Arizona)										
Urban	0.01	0.03	0.02	0.01	0.02	0.02	0.02	0.01	0.02	0.02
Suburban	0.15	0.19	0.09	0.10	0.08	0.20	0.14	0.09	0.23	0.25
Rural	0.84	0.78	0.89	0.90	0.90	0.78	0.85	0.90	0.75	0.73
Trojan (Oregon)										
Urban	0	0.01	0.01	0.01	0	0.01	0	0.02	0	0.01
Suburban	0.16	0.11	0.13	0.09	0.19	0.14	0.18	0.10	0.35	0.17
Rural	0.84	0.88	0.86	0.90	0.80	0.85	0.82	0.89	0.64	0.82

[a]These reactors were chosen as representative of regions throughout the country.

Table F-9. Fraction of travel in population zones from sources of high-level waste

Waste source	Richton Dome Truck	Richton Dome Rail	Deaf Smith Truck	Deaf Smith Rail	Davis Canyon Truck	Davis Canyon Rail	Yucca Mt. Truck	Yucca Mt. Rail	Hanford Truck	Hanford Rail
Hanford										
Urban	0.01	0	0.01	0.01	0	0	0	0.01	NA[a]	NA
Suburban	0.16	0.11	0.12	0.10	0.19	0.15	0.18	0.10	NA	NA
Rural	0.84	0.89	0.87	0.89	0.81	0.84	0.82	0.89	NA	NA
Idaho National Engineering Laboratory										
Urban	0	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0	0
Suburban	0.15	0.10	0.10	0.11	0.21	0.22	0.19	0.11	0.15	0.12
Rural	0.85	0.90	0.89	0.88	0.78	0.77	0.80	0.88	0.85	0.88
Savannah River Plant										
Urban	0.01	0.03	0.01	0.02	0	0.02	0.01	0.02	0	0.01
Suburban	0.30	0.26	0.23	0.21	0.22	0.19	0.17	0.21	0.19	0.17
Rural	0.69	0.72	0.76	0.78	0.77	0.79	0.82	0.78	0.81	0.82
West Valley										
Urban	0.01	0.03	0	0.02	0.01	0.02	0.01	0.02	0.01	0.01
Suburban	0.32	0.33	0.30	0.21	0.22	0.18	0.20	0.21	0.21	0.17
Rural	0.67	0.64	0.70	0.78	0.77	0.80	0.79	0.78	0.78	0.82

[a]NA = not applicable.

Table F-10. Number of shipments to a repository from each reactor site

Reactor	100% Truck	100% Rail	Reactor	100% Truck	100% Rail
Farley 1	120	18	Millstone 1	804	111
Farley 2	46	7	Millstone 2	805	106
Palo Verde 1	511	72	Millstone 3	36	6
Palo Verde 2	484	70	Monticello	693	96
Palo Verde 3	448	63	Prairie Island 1	650	92
Arkansas Nuclear One 1	762	108	Prairie Island 2	631	90
Arkansas Nuclear One 2	187	27	Fort Calhoun 1	534	76
Calvert Cliffs 1	893	127	Humboldt Bay	86	12
Calvert Cliffs 2	853	122	Diablo Canyon 2	236	34
Pilgrim 1	761	105	Diablo Canyon 1	279	40
Robinson 2	581	83	Susquehanna 1	652	90
Brunswick 2	799	111	Susquehanna 2	614	85
Brunswick 1	791	109	Peach Bottom 2	1126	156
Perry 1	806	110	Peach Bottom 3	1126	156
Perry 2	747	104	Limerick 1	679	95
Dresden 1	136	18	Limerick 2	421	59
Dresden 2	909	126	Trojan	330	18
Dresden 3	825	114	Fitzpatrick	614	107
Quad-Cities 1	862	119	Indian Point 3	714	102
Quad-Cities 2	815	113	Seabrook 1	486	69
Zion 1	858	122	Seabrook 2	320	46
Zion 2	824	117	Salem 1	791	113
LaSalle 1	572	79	Salem 2	764	109
LaSalle 2	572	79	Hope Creek 1	509	71
Byron 1	638	88	Ginna	503	71
Byron 2	631	86	Rancho Seco 1	721	103
Braidwood 1	568	83	Summer	12	2
Connecticut Yankee	702	100	San Onofre 1	203	29
Indian Point 1	80	11	San Onofre 2	306	44
Indian Point 2	762	108	San Onofre 3	347	50
Big Rock Point	104	14	South Texas Project 1	594	82
Palisades	796	113	South Texas Project 2	592	82
Midland 2	373	49	Browns Ferry 1	699	135
Midland 1	334	46	Browns Ferry 2	695	140
La Crosse	143	19	Browns Ferry 3	986	137
Fermi 2	609	85	Sequoyah 1	444	46
Oconee 1	759	108	Sequoyah 2	425	42
Oconee 2	612	87	Watts Bar 1	518	74
Oconee 3	779	111	Watts Bar 2	524	74
McGuire 1	115	17	Bellefonte 1	444	64
McGuire 2	73	11	Bellefonte 2	327	47
Beaver Valley 1	735	104	Hartsville A1	463	65
Beaver Valley 2	272	39	Hartsville A2	328	45
Crystal River 3	676	96	Yellow Creek 1	90	13
Turkey Point 3	695	99	Yellow Creek 2	50	8
Turkey Point 4	694	99	Comanche Peak 1	412	58
St. Lucie 1	894	113	Comanche Peak 2	368	53
St. Lucie 2	486	70	Davis-Besse 1	248	31
Hatch 1	312	43	Callaway 1	360	51
Hatch 2	289	40	Vermont Yankee	675	93
Vogtle 1	547	78	Surry 1	748	102
Vogtle 2	416	60	Surry 2	620	77
River Bend 1	465	65	North Anna 1	365	47
Clinton 1	528	74	North Anna 2	295	38
Cook 1	948	135	WNP 2	650	90
Cook 2	933	133	WNP 1	394	56
Arnold	562	79	WNP 3	617	89
Oyster Creek	777	108	Point Beach 1	620	88
Wolf Creek	191	27	Point Beach 2	591	84
Shoreham	270	38	Kewaunee	634	90
Waterford 3	421	61	Yankee	340	48
Maine Yankee	980	140	Brunswick 2	72	10
Three Mile Island 1	723	103	Brunswick 1	80	11
Grand Gulf 1	247	35	Morris BWR	150	20
Grand Gulf 2	340	48	Morris PWR	175	25
Cooper	771	107	West Valley BWR	17	2
Nine Mile Point 1	700	97	West Valley PWR	60	8
Nine Mile Point 2	243	33		70,553	9927

The numbers of radiological fatalities predicted for the public from waste transportation to each site are given below. The ranges account for the uncertainty associated with the second repository and the uncertainty associated with models and data, as discussed above.

Site	Predicted fatalities (range)
Davis Canyon	3.5 (0-4.9)
Deaf Smith	2.9 (0-4.1)
Richton Dome	2.4 (0-3.4)
Hanford	4.3 (0-6.1)
Yucca Mountain	4.1 (0-5.7)

As is the case for all transportation health-and-safety objectives, the number of fatalities is proportional to the total distance. Thus, Richton Dome, being the closest to the sources of waste, has the lowest level of impact and Hanford, being the most distant, has the highest level.

The impacts reported above are slightly higher than those reported in Appendix A of the environmental assessments because they reflect an assumed dose-effect relationship of 280 health effects per million man-rem rather than 100 health effects per million man-rem.

F.1.6 RADIOLOGICAL FATALITIES IN WASTE-TRANSPORTATION WORKERS

The performance measure is the predicted number of radiological fatalities in waste-transportation workers. The method of predicting health effects was described in the preceding section, which discusses radiological fatalities in the public. Basically, it involves the use of unit-risk factors. This approach relies on a set of factors developed by using an analytical model known as RADTRAN to obtain the risk per unit distance traveled for each type of shipment (Wolff, 1984). Unit risk factors are presented in terms of the population dose (man-rem) per unit of distance traveled. Once the unit risk factors are calculated, they can be applied by simply multiplying them by the total distance traveled. Thus, the single most important factor in the calculations is the shipment distance. The total distance traveled to each of the sites given the assumption that 70 percent of the waste is transported by rail and 30 percent by truck, together with the predicted number of fatalities, is shown below.

Site	Total distance (millions of miles)	Predicted fatalities (range)
Davis Canyon	61.4	0.72 (0-1.0)
Deaf Smith	51.6	0.64 (0-0.90)
Richton Dome	41.3	0.52 (0-0.73)
Hanford	79.3	0.90 (0-1.3)
Yucca Mountain	74.8	0.81 (0-1.1)

The ranges account for the uncertainty associated with the second repository (+40 and -46 percent) and the uncertainty associated with models and data (+0 and -100 percent), as discussed in Section F.1.5. It was assumed that the dose-effect relationship is 280 fatalities per million man-rem.

F.1.7 NONRADIOLOGICAL FATALITIES IN WASTE-TRANSPORTATION WORKERS

This performance measure is the predicted number of nonradiological fatalities in transportation workers. All of these fatalities would result from transportation accidents. (The effects of air pollution were also considered, but are insignificant in comparison with accidents.) The factors that affect the number of fatalities are the same as those described in Section F.1.5 except for the unit-risk factors. Unit-risk factors for nonradiological effects are evaluated from accident-consequence data collected from actual transportation records. The relevant unit-risk factors are given in Table F-11.

Table F-11. Nonradiological risk factors for shipments from waste sources to repository[a]

Mode	Zone	Hazard group	Spent fuel[b]	High-level waste[b]	
				Defense	Commercial
Truck	Rural	Public fatalities from air pollution	0	0	0
Truck	Rural	Worker fatalities from transportation accidents	1.50E-08[c]	1.50E-08	1.50E-08
Truck	Rural	Public fatalities from transportation accidents	5.30E-08	5.30E-08	5.30E-08
Truck	Suburban	Public fatalities from air pollution	0	0	0
Truck	Suburban	Worker fatalities from transportation accidents	3.70E-09	3.70E-09	3.70E-09
Truck	Suburban	Public fatalities from transportation accidents	1.30E-08	1.30E-08	1.30E-08
Truck	Urban	Public fatalities from air pollution	1.00E-07	1.00E-07	1.00E-07
Truck	Urban	Worker fatalities from transportation accidents	2.10E-09	2.10E-09	2.10E-09
Truck	Urban	Public fatalities from transportation accidents	7.50E-09	7.50E-09	7.50E-09
Rail	Rural	Public fatalities from air pollution	0	0	0
Rail	Rural	Worker fatalities from transportation accidents	1.81E-09	1.81E-09	1.81E-09
Rail	Rural	Public fatalities from transportation accidents	2.64E-08	2.64E-08	2.64E-08
Rail	Suburban	Public fatalities from air pollution	0	0	0
Rail	Suburban	Worker fatalities from transportation accidents	1.81E-09	1.81E-09	1.81E-09
Rail	Suburban	Public fatalities from transportation accidents	2.64E-08	2.64E-08	2.64E-08
Rail	Urban	Public fatalities from air pollution	1.30E-07	1.30E-07	1.30E-07
Rail	Urban	Worker fatalities from transportation accidents	1.81E-09	1.81E-09	1.81E-09
Rail	Urban	Public fatalities from transportation accidents	2.64E-08	2.64E-08	2.64E-08

[a] Risk factors given per kilometer. To convert factors to risk per mile multiply by 1.609.
[b] Unit risk factors for general-commerce transportation by truck or rail; units are per kilometer for truck transportation and per railcar-kilometer for rail transportation.
[c] Computer notation is used in this table. Thus, 1.50E-08 = 1.5×10^{-8}.

The predicted numbers of fatalities for each site are given below. The ranges account for the uncertainty associated with the second repository (+40 and -46 percent) and the uncertainty associated with models and data (+15 and -15 percent).

Site	Predicted fatalities (range)
Davis Canyon	2.1 (0.96-3.4)
Deaf Smith	1.6 (0.73-2.6)
Richton Dome	1.3 (0.6-2.1)
Hanford	2.7 (1.2-4.3)
Yucca Mountain	2.5 (1.1-4.0)

F.1.8 NONRADIOLOGICAL FATALITIES INCURRED BY THE PUBLIC FROM WASTE TRANSPORTATION

One of the health-and safety objectives is to minimize nonradiological effects on the public from the transportation of waste, and the performance measure is the number of nonradiological fatalities, which are assumed to result from accidents. Nonradiological fatalities do not depend on the nature of the cargo; they are effects that could occur in any tranportation accident, whatever the commodity that is being transported.

The risk factors are given in Table F-11. The results of the analysis are presented below. The ranges account for the uncertainty associated with the second repository (+40 and -46 percent) and the uncertainty associated with models and data (+15 and -15 percent).

Site	Predicted fatalities (range)
Davis Canyon	8.4 (3.9-13.5)
Deaf Smith	6.7 (3.1-10.8)
Richton Dome	5.3 (2.4-8.5)
Hanford	11 (5-17.7)
Yucca Mountain	10.2 (4.7-16.4)

As is the case for all the health-and-safety objectives, there is a strong correlation between the impacts and distance from the sources of waste.

F.2 ENVIRONMENTAL IMPACTS

There are three environmental objectives: (1) to minimize aesthetic impacts; (2) to minimize archaeological, historical, and cultural impacts; and (3) to minimize biological impacts. Impacts caused by both the repository and by waste transportation through the affected area are considered in the analysis.

F.2.1 AESTHETIC IMPACTS

Since there is no direct measure of aesthetic impacts, surrogate measures of performance were developed, and a scale of 0 to 6 was constructed (Table 4-2). The surrogate measures are based on three fundamental factors identified in the influence diagram for aesthetic quality (Appendix E): the presence of land areas designated for their special aesthetic qualities, incremental visual changes, and the introduction of incremental undesirable noise. On the constructed scale, 0 corresponds to virtually no degradation of aesthetic quality and 6 corresponds to a major aesthetic degradation.

The presence of land areas designated for their special aesthetic qualities recognizes that particular areas may be more sensitive to changes in aesthetic quality than other areas. The factors that affect this sensitivity include the type of resource area at risk and the use of the resource area. Examples of areas so designated are components of the National Park System, the National Wildlife Refuge System, the National Wild and Scenic Rivers System, the National Wilderness Preservation System, National Forest Land, or a comparably significant State resource area. The aesthetic characteristics of such areas are typically among the qualities that are the basis for their protected status. Subsequent uses and enjoyment of such areas are also determined by aesthetic characteristics. The presence of such designated or unique resource areas in the area affected by the repository and the local transportation system must therefore be considered together with the extent of the area affected.

Incremental visual changes can be measured by the visibility reduction caused by project-related pollutant emissions, skyglow, and the degree of contrast with the existing visual setting. The criteria that can be used in assessing "contrast" include the extent to which the natural environment is physically altered or destroyed, nonconformity with the existing environment through the intrusion of elements out of scale or out of character with the existing physical environment, the division of a valued area (i.e., a park), incompatibility with the existing character or uses of land in the area, and the impairment of existing conditions.

The degree to which any noise from the project is undesirable can be established from noise criteria developed for particular types of sensitive receptors. For example, the EPA has promulgated noise guidelines for the protection of human hearing loss and for the protection of the public from noise in normally quiet areas. In addition, the U.S. Forest Service (USFS) has established audibility guidelines for various types of recreational activities. Since the sensitive receptors vary from site to site, the criteria used to determine the significance of noise intrusion also differ. The criteria applied for the noise assessments are described in the environmental assessments for the sites (DOE, 1986a-e, Sections 4.2.1.4 and 5.2.6).

Presented on the next page are the scores (impact levels) for each site and the bases for these scores. The scores are based on the extent, duration, and intensity of visual and noise effects, the sensitivity of a resource area to impacts, and the cumulative and synergistic effects on the aesthetic character of the site and nearby areas. The first score is the base-case impact level. The range shows the scores for the low and the high impact levels.

Site	Impact level (range)
Davis Canyon	6 (6-6)
Deaf Smith	4 (3-5)
Richton Dome	4 (1-5)
Hanford	1 (1-2)
Yucca Mountain	4 (1-5)

Davis Canyon

At the Davis Canyon site, considerable aesthetic degradation would result from introducing a major industrial facility in a remote area that is highly scenic and is used mainly for recreation. There are several unique aesthetic resources in the vicinity of the Davis Canyon site, including the Canyonlands National Park, the Bridger Jack Mesa Wilderness Study Area, the Newspaper Rock State Historical Monument, and various recreation areas managed by the Bureau of Land Management (BLM). All of these resource areas would experience visual or noise effects.

Project activities would be visible and audible in the Canyonlands National Park. From various isolated points in the eastern district of the Park, the facilities of the repository, the access road, and the rail route would contrast visually with the surrounding area and attract attention. Project-related noise would exceed the USFS audibility threshold at the nearest park boundary.

In the northern portion of the Bridger Jack Mesa and the Newspaper Rock State Historical Monument, the noise from traffic on Utah-211 would exceed the USFS audibility threshold. The repository, the access road, and the rail route would be visible from the Bridger Jack Mesa.

The access road and the rail route would be visible from Canyonlands overlooks and BLM overlooks. Depending on the rail-route alternative that is selected, visual contrast could occur at the Arches Visitors Center, the Dead Horse State Park Overlook, or the State of Utah Kane Springs Rest Area and the Wilson Arch Viewpoint.

Parts of the repository would be visible from portions of Harts Point, Hatch Point, and the access road to Needles Overlook. The repository, the access road, and the rail route would be visible from the Davis Canyon jeep trail and along portions of Utah-211.

Because of the predicted visual and noise impacts and the impacts on the various unique resource areas, the Davis Canyon site is assigned a base-case impact level of 6 for the aesthetic-impact performance measure (the high-impact score is also 6). Considering the number of unique resource areas that could be affected, the duration of the impacts, the magnitude of the impacts (i.e., ratings), and the natural aesthetic setting, it is unlikely that any major impacts could be entirely eliminated or mitigated to insignificant levels. Thus, even the low-impact score is 6.

Deaf Smith

An industrial complex in an open agricultural setting would greatly contrast with the natural setting.

Noise levels at some nearby residences may exceed the EPA guideline for the average day-and-night noise levels (L_{dn} = 55 decibels). However, this guideline is likely to be exceeded only during construction. The base-case score for the Deaf Smith site is 4. This score is based on a long-term visual contrast and short-term adverse noise levels.

If the noise generated by repository operation is greater than expected, the noise levels at nearby residences may exceed the EPA guideline, resulting in a major noise effect. A major visual effect combined with a major noise effect would give the Deaf Smith site a high-impact score of 5. If additional noise mufflers are used or if project activities are sited farther away from residences, noise effects could be disminished, but the visual contrast would remain. The low-impact score for the Deaf Smith site is therefore 3.

Richton Dome

For the Richton Dome site, the base-case score on the aesthetic-quality performance measure is 4. Visual and land impacts would occur from the development of a rural landscape. Portions of the headframes for repository shafts would be visible from Mississippi State Highway 42. During site characterization and repository construction, two residences would experience noise exceeding the EPA guideline for day-and-night noise levels (55 decibels). Depending on the routing along local highways, four residences may be affected by repository-traffic noise.

The low-impact score for Richton Dome is 1. This level could be obtained if the repository is sited in such a way that it could not be seen from State Highway 42 and if additional noise mufflers are used on equipment.

It is, however, possible that the repository or transportation routes may be sited where they could be more visible from State Highway 42 or from another key observation point, such as the DeSoto National Forest. It is also possible that noise levels could exceed the EPA guideline for longer durations. Thus, the high-impact score for Richton Dome is 5.

Hanford

Since at Hanford the repository would be constructed on a site that is already used as a DOE center for nuclear research and development, the expected incremental aesthetic effects at the Hanford site would be minimal. Existing activities already generate noise and visual impacts at the site. The noise generated by the repository project would not exert any effects distinguishable from those of current aircraft and surface traffic. The repository may be partly visible from Route 240, but it would be similar to other structures in the area. The base-case score as well as the low-impact score for the Hanford site is therefore 1. Even if both adverse visual or noise impacts do occur, it is still not likely that noise levels would be unacceptable or that visual contrasts would be seen. The high-impact score for Hanford is therefore 2.

Yucca Mountain

Visual impacts at the Yucca Mountain site would be minimal because most project activities would not be visible from population centers or public recreation areas. The rail route, the transmission line, and the access road, as well as some site-characterization activities, may be visible from U.S. Highway 95. Since the land in the area is used by the U.S. Air Force and by the DOE, the activities of the project would not be incompatible with the current uses of the area.

The base-case score for Yucca Mountain is 4. It is based on rail-transportation noise that would exceed the EPA guideline of 55 decibels at residential areas and at Floyd Lamb State Park.

The high-impact score for Yucca Mountain is 5. This score would be assigned if transportation routes dissected BLM land used for recreational purposes, resulting in a high visual contrast and thus adding a major visual impact to a major noise impact. A low impact level of 1 could be obtained for this site if the railroad could be so routed that it would not traverse or affect residential areas or the State park.

F.2.2 ARCHAEOLOGICAL, HISTORICAL, AND CULTURAL IMPACTS

One of the objectives of siting is to minimize adverse impacts on significant archaeological, historical, and cultural properties; these impacts may be directly or indirectly attributable to the repository and waste transportation. The performance measure for this objective is a constructed scale of 0 to 5, where 0 means no impact and 5 means a very serious degradation of archaeological, historical, or cultural properties (see Table 4-3). The assignment of scores is based on a quantitative evaluation of the significance of properties, the number of properties that would be affected, the degree of impact, and amenability to impact mitigation.

The repository project--that is, the repository itself and the local transportation network--has the potential to affect significant historical properties through the alteration or destruction of the property, the alteration of the surrounding environment, and the introduction of elements that are out of character with the property. Such effects may result from the construction or operation of the repository, the construction of transportation access routes or the waste-transportation operations, or an increase in population and the concomitant increase in commuting.

The scores (impact levels) assessed for each site are shown below for the base case as well as the low- and the high-impact cases.

Site	Level of impact (range)
Davis Canyon	3 (2.5-5)
Deaf Smith	1 (0-2.5)
Richton Dome	0.5 (0-1)
Hanford	0.5 (0.5-3)
Yucca Mountain	2 (2-3.5)

Davis Canyon

Davis Canyon is in an area that is exceptionally rich in archaeological remains. Despite the absence of a systematic survey in the project area, extensive data collection has been conducted in the region, and several hundred aboriginal archaeological sites have been recorded in the area. The area has a diverse and abundant base of cultural resources, with sites spanning from the Paleo-Indian (9500 to 5500 B.C.) to the Euro-American Historic (A.D. 1765 to present) periods. Archaeological sites include chipping stations, transient and alcove camps, storage sites, open and alcove habitations, rock shelters, rock art, and archaeoastronomy sites. The rock-art sites--particularly those in the Newspaper Rock State Historical Monument--are considered by some to be of "world class."

The rock-art and the archaeoastronomy sites are of major concern. Although the individual rock-art sites may not be impressive, taken as a whole they are an important record of the past. The archaeoastronomy sites provide information about the aboriginal understanding of celestial events. In both cases, the relationship of the site to similar sites in the environmental context is critical to their significance.

Historical sites in the Davis Canyon area have the potential for containing information on early exploration, settlement, ranching, and mining, as well as the place of the area in the history of the region.

Davis Canyon was assigned a base-case score of 3 because it is expected that some sites of major significance would be adversely affected. If those impacts could be adequately mitigated, the score could be as low as 2.5. However, it is possible that the impacts on a number of major sites would be so severe as to require a score of 5.

Deaf Smith

The Deaf Smith site is in a region that shows evidence of human occupation from Paleo-Indian (12,000 to 8000 years before the present) to Historic times (A.D. 1600 to the present). There has been no surface reconnaissance of archaeological sites in the immediate vicinity of the site, and long agricultural use makes it likely that much surface evidence has been obliterated. However, given the density of sites nearby, there is a high potential for undiscovered sites, especially near water sources (including the two playa lakes at the site).

Similarly, no historical sites have been recorded, but the potential for undiscovered historical resources is high. The site may contain historical aboriginal sites associated with water resources, Comanchero and Cibolero trails located north of Palo Duro Creek, Pastores occupational sites along stream drainages, evidence of ranching and farming, and a historical trail.

Deaf Smith is assigned a base-case score of 1 for archaeological impacts. It is probable that at least five properties of minor importance would be discovered, but it is reasonable to assume that the impacts would be amenable to mitigation. The low-impact score could be 0; it is possible that no sites would be discovered. However, if the area does yield archaeological and historical material, the high-impact score could be 2.5.

Richton Dome

The area of the Richton Dome and the surrounding vicinity are almost unknown archaeologically. It is unclear whether the dearth of information is due to the lack of sites or to the lack of investigation.

The potential for discovering sites in this area is low. Extensive plowing and forestry preclude the possibility of extensive surface remains, but buried remains in colluvial and alluvial deposits are possible.

It is expected that historical remains include such buried deposits as house foundations or cisterns. Standing structures may include vernacular architecture of house, barn, and outbuildings. Archaeological remains in the region suggest occupation for as long as 17,000 years, with three separately recognized eras: Paleo-Indian, Indian, and Archaic.

The scores for Richton Dome are 0.5, 0, and 1 for the base case, low impacts, and high impacts, respectively.

Hanford

The Columbia River region of Washington State was densely inhabited during aboriginal times, but most prehistoric sites have been destroyed through vandalism and development. Nine archaeological properties have been identified on the Hanford reservation, but none is within the nominated Hanford site.

Archaeological surveys of the Hanford site concluded that the repository would not affect significant historical properties. Local specialists have contested this conclusion, suggesting that there are additional sites that may be directly or indirectly affected by the repository. Furthermore, local Indian groups--notably the Yakima Indian Nation--claim religious significance for Gable Mountain.

The base-case and the low-impact scores for Hanford are both 0.5. Because of Indian claims for Gable Mountain, a higher score, 3, could be considered, but it would be necessary to demonstrate the presence of a major site of religious significance.

Yucca Mountain

The extensive field inventory that has been conducted in the vicinity of Yucca Mountain shows that generally the area is very rich in resources. The richness is attributable largely to preservation: since the area is dry, materials do not disintegrate rapidly. Furthermore, the area has not been extensively disrupted over time.

A total of 178 prehistoric aboriginal sites were identified in the area, representing use by small and highly mobile groups or bands of aboriginal hunter-gatherers. Among them are 21 campsites and 141 extractive locations--the remains of limited, task-specific activities associated with hunting, gathering, and processing wild plants.

The historical resources in the area include historical trails, mining camps and mines, ghost towns, ranches, and Mormon settlements.

Impact levels for Yucca Mountain depend not so much on the number of sites present as on the potential for avoiding or mitigating adverse impacts on those sites. The regulations of the Advisory Council (36 CFR Part 800) state that a site significant for the data it contains can be excavated, and the data extracted, without major impact on the site (or the reason for its significance). Given that standard, it is possible to say that, despite the large number of sites, it may be possible to avoid major impacts on most of the sites that may be affected by the repository.

Given the assumption that most effects would be minimal but given also the great number of sites that may be affected, the base-case score for Yucca Mountain is 3. However, if it is possible to keep all impacts minor, the impact level could be as low as 2. Alternatively, if the impacts are not subject to mitigation, the level could be as high as 3.5.

F.2.3 IMPACTS ON BIOLOGICAL RESOURCES

Biological degradation can be considered in terms of adverse effects on habitats or species. The project has a potential for directly altering habitats through land clearing, stream realignment, streambank disturbance, or the filling and draining of wetlands. Habitats may be affected by the placement of structures in such a way that they may act as physical or behavioral barriers to wildlife or may disrupt the continuity of an ecological unit. Another potential source of habitat disruption is the discharge of effluents that alter physical or chemical conditions. Wildlife may be directly affected by accidents resulting in roadkills; by increased hunting, fishing, or poaching pressures; or by increased noise, lighting, or disturbances associated with the presence of people.

Since there is no one quantifiable measure of overall biological impacts and no one type of impact is considered to be truly representative of resource degradation, the performance measure is a scale constructed to address a range of effects (see Table 4-4). On this scale, 0 means no damage to habitats or species and 5 means the destruction of threatened, endangered, rare, or sensitive species or their habitats, with adverse effects on the regional abundance. To determine where the site-specific effects fall within the scale, the evaluation considers the possibility of an effect, the magnitude of the potential effect, and the importance of the effect. The magnitude of the effect is evaluated in terms of the numbers of affected species or habitats, the number or percentage of a species or habitat area that is affected, and the percentage of the regional population base that is affected. The importance of the effect is evaluated in terms of the type of species or habitat affected (i.e., threatened or endangered).

Since there is no one quantifiable measure of overall biological impacts and no one type of impact is considered to be truly representative of resource degradation, the performance measure is a scale constructed to address a range of effects (see Table 4-4). On this scale, 0 means no damage to habitats or species and 5 means the destruction of threatened, endangered, rare, or

sensitive species or their habitats, with adverse effects on the regional abundance. To determine where the site-specific effects fall within the scale, the evaluation considers the possibility of an effect, the magnitude of the potential effect, and the importance of the effect. The magnitude of the effect is evaluated in terms of the numbers of affected species or habitats, the number or percentage of a species or habitat area that is affected, and the percentage of the regional population base that is affected. The importance of the effect is evaluated in terms of the type of species or habitat affected (i.e., threatened or endangered).

The base-case scores for the five sites are given below; the ranges show the low- and high-impact scores.

Site	Level of impact (range)
Davis Canyon	3.5 (2.67-4.5)
Deaf Smith	2.33 (1.5-3)
Richton Dome	2.67 (2-3.5)
Hanford	2.33 (1-3.5)
Yucca Mountain	2 (1-2.67)

Davis Canyon

Much of the land around the Davis Canyon site has been recommended for, or is already dedicated to, wilderness areas, national parks, and the like. The area is part of the Inter-Mountain Sagebrush Floral Province, where the desert shrub and pinyon pine-juniper woodlands tend to dominate. No unique plant ecosystems have been identified in Davis Canyon. Both the diversity and the productivity of the natural vegetation and wildlife are low. Much of the site is native pasture supporting open-range livestock grazing.

There are no aquatic communities or wetlands on the site, but wetlands occur in narrow zones along nearby Indian Creek. The upper 12 mile section of Indian Creek has been classified by the U.S. Fish and Wildlife Service as a Class 2 (high-priority) fisheries resource.

No threatened or endangered species have been found at the site, but the area is favorable for a variety of federally designated species. Two plants with threatened-or-endangered status may be present near the areas proposed for site-characterization field studies. A peregrine falcon nest has been observed in the Canyonlands National Park, and two more have been seen near Moab. In addition, a pair of peregrines has been sighted along North Cottonwood Creek. Bald eagles are known to roost along the Colorado River. Three endangered species of fish--the Colorado squawfish, the humpback chub, and the bonytail chub--occur 25 miles downstream from the Davis Canyon site.

Sensitive species also occur in the area. Raptors--including golden eagles, red-tailed hawks, prairie falcons, and great horned owls--nest in the vicinity of Davis Canyon. Mule deer overwinter in Davis Canyon. Areas considered for transportation and utility corridors contain populations of desert bighorn sheep, mule deer, and pronghorns, as well as the above-mentioned federally protected species. Nearby Hatch Point is the site of two fawning grounds for pronghorns. It also contains habitat for the sage grouse, which is scarce in the area. Kane Springs Canyon provides riparian and bighorn sheep habitat, and several areas to the south of Harts Draw are considered valuable pronghorn range. Drainages near the Colorado River provide the most sensitive biological resources in the ara in the form of valuable riparian habitats.

The repository project would have several impacts on the natural environment. Usage of the Canyonlands wilderness and recreation areas may increase. Locally, temporary loss of vegetative cover would occur. Impacts on wildlife would include temporary displacement or disturbance of small mammals and birds. Drilling would be conducted 0.6 to 9 miles from golden eagle nests, and the construction of access roads to the drill sites may also disturb the birds. In addition, noise or human presence may affect the foraging of the bald eagles and peregrine falcons nesting in the area. However, no depletion of these endangered species is expected because of the distance of their known roosts or breeding areas. A bald eagle nest known to be 2 miles away from any project activity may experience some disturbance due to noise and the presence of people.

Impacts from salt deposition are expected to be minimal because most of the deposition would be contained within the site. Offsite deposition is expected to be insignificant.

Access-road construction and seismic survey lines would destroy some habitats and may affect threatened and endangered species (peregrine falcons, bald eagles, and black-footed ferrets). The riparian habitats around Indian Creek would be disrupted by field testing and utility crossing. The drainage that provides riparian habitat near the Colorado River would also be disturbed. Realignment of Indian Creek for the Utah-211 bypass would disrupt riparian habitat.

The Utah-211 bypass may also affect the mule deer. The proposed water pipeline may interfere with the movement of bighorn sheep, and the removal of water by this pipeline from the Colorado River may jeopardize the endangered Colorado squawfish. Impacts on floodplain biota would include the clearing of local vegetation adjacent to the Davis Canyon wash and at the Indian Creek crossing point. Because almost all drainages are ephemeral desert washes, very limited impacts are expected. Increased human presence may cause some disturbance and displacement of wildlife from adjoining floodplain areas. Impacts on water quality would be limited to local and temporary increases in sediment loads from land alterations and disturbances. Site runoff and discharge would be controlled. No adverse effects from windblown salt are expected.

Davis Canyon is assigned a base-case score of 3.5. The riparian habitats that would be affected are not common to the area. The transportation corridors and water pipeline may affect several threatened or endangered species and would interfere with the access of mule deer and pronghorns to their wintering and fawning grounds. The potential effects on the riparian habitats, which are biologically sensitive resource areas, place the impact level above 3. Although there may be some effects on threatened and endangered species, their regional abundance is not likely to be threatened, and thus the base-case score would not be higher than 4.

The high-impact score for Davis Canyon is 4.5. If the riparian habitats are greatly affected, there may be a threat to the regional abundance of the threatened and endangered species that rely on them as well as to other sensitive species in the area.

The low-impact score is 2.67. It would be assigned if the potential impact on the riparian habitats and on the threatened and endangered species are diminished by avoiding known nesting or foraging areas and using buffers.

Deaf Smith

The Deaf Smith site is on land that is predominantly prime farmland. The area is semiarid to subhumid, with steppe or shortgrass prairie cover where it is not cultivated. Both at the site and in its vicinity there are playas and ephemeral-stream wetlands, which are ecologically important. (There are 17 playas in the vicinity, and 12 of them have already been heavily modified.) There are seven threatened or endangered species in the site vicinity: two reptiles (the Texas horned lizard and the Central Plains milk snake), four birds (the bald eagle, the whooping crane, the American peregrine falcon, and the Arctic peregrine falcon), and one mammal (the black-footed ferret). There are no critical habitats on the site or in its vicinity. State-protected species occurring in the vicinity are the osprey and the woodstock.

Wildlife in the area may be adversely affected by increased human presence, traffic, noise, dust, and erosion. Although there would be no permanent loss of habitats, raptors may experience a temporary decrease in foraging habitat. Three of the playas would be drilled.

The repository is not expected to affect water quality, although degradation due to sediment loading may occur for short periods of time. Effects on aquatic biota are expected to be minor, as most runoff would be handled at the site. During construction, no effects on surface-water quality are expected because sedimentation would be controlled and impacts due to salt dispersal would be insignificant. Most of the windblown-salt deposition is expected to occur in the controlled area, and hence no significant effects on soil productivity are expected. Effects on water are expected to be minimal because of the measures that would be used in handling salt.

The Deaf Smith site has been assigned a base-case score of 2.33. Sensitive playas would be affected, although the three playas that would be drilled have been heavily modified. Threatened or endangered species as well as sensitive and State-protected species may be affected by the loss of habitat. However, since much of this area is in agricultural use, many of the more sensitive species would already have been affected and dislocated. Although some sensitive resources would be affected and some threatened or endangered species may be affected, it is more likely that most of the impacts would be incurred by more-common and less-sensitive species and biological resources.

The low-impact score for Deaf Smith is 1.5. The playas that would be drilled may have been so heavily modified that they are of limited use in contributing to the variety of ecosystems in the area. In addition, if there are few or no threatened or endangered species in the affected area, then most of the impact would be felt by the more-common species.

The high-impact score for Deaf Smith is 3. Although there is a potential to affect sensitive species and threatened or endangered species in the area, the natural ecosystem has already been so modified as to limit the impacts. Although the potential for future negative impacts is not negligible, the initial impacts of ecosystem modification in the area have already occurred from agricultural activities.

Richton Dome

The Richton Dome site is characterized as a longleaf-slash pine habitat. It is drained by several streams and dotted by wetlands. No unique ecosystems have been identified in the area of the site, nor are there any known threatened or endangered species or critical habitats at the site. However, colonies of the cockaded woodpecker are found 10 miles south of the site, and the American alligator occurs 10 to 15 miles southwest of the site; both are on the Federal list of endangered species. The bald and golden eagles and the graybat also occur in the vicinity. The area contains three rare but not protected species and five State-protected species. Twenty-nine threatened or endangered species of plants could also occur in the area, but there are no known designated critical habitats for flora in the area. The Chickasawhay Wildlife Management Area of the DeSoto National Forest is 3 miles north of the dome.

During site characterization and repository construction, some wetlands would be destroyed. Adjoining wetlands would be disturbed and broken up by access roads. A creek would be relocated, and another would be traversed by a bridge. There would be a general loss of vegetation and habitat.

The habitats of the bald eagle and the graybat may be affected. The development of access corridors may affect potential habitats of the red cockaded woodpecker. The cumulative effects of repository siting, construction, and operation may be adverse to various species in the area and result in range abandonment, decreased productivity, and a decrease in the size of fish and wildlife populations, including migratory birds and rare or endangered species.

Most of the windblown-salt deposition is expected to occur in the controlled area, and therefore minimal effects on soil productivity are expected. Effects of the windblown salt on water quality would be small, and no adverse effects on vegetation are expected.

There would be permanent loss of some aquatic habitats because of stream diversion, alterations, and drainage. The seismic refraction lines may cross floodplain areas, creating temporary breaks in these ecosystems. Water quality would be temporarily affected by increased sedimentation, and the loss of some organisms is unavoidable. However, the impacts would be localized.

Richton is assigned a base-case score of 2.67. The wetlands are a sensitive biological resource that would be affected. Since there are many species with Federal status as threatened or endangered, the potential for impact is relatively high. The relocation of various waterways would affect the threatened or endangered species in the area. If the access lines need to cross the habitat of the red cockaded woodpecker or the American alligator, then the potential for affecting a threatened or endangered species would be increased. However, there appears to be little threat of affecting the regional abundance of the threatened or endangered species.

The low-impact score for the Richton Dome site is 2. At the least, the repository would affect some wetlands, which are biologically sensitive. The high-impact score for the Richton Dome site is 3.5. If the wetlands are discovered to be critically tied to a sensitive species or a threatened or endangered species, then a score of 3.5 is possible. If the destruction of wetlands would bring the abundance of a species dependent on them down to a critical level, then this site should potentially rate fairly low.

Hanford

The Hanford site is in a shrub-steppe ecosystem--a relatively fragile environment that contains separate ecological communities. There are no naturally occurring surface-water systems or wetlands on the site. However, manmade aquatic areas on the site attract a variety of birds and mammals.

No federally designated threatened or endangered species are known to nest at the site or to use it as a critical habitat. The bald eagle and the peregrine falcon have been infrequently seen in the area, and three birds that are candidates for Federal protection nest at the site or nearby: the long-billed curlew, Swainson's hawk, and the ferruginous hawk; the latter is classified as threatened by the State of Washington.

The site contains no plants with Federal threatened or endangered status or their critical habitats. However, several species that do occur at the site are being considered for threatened status, and two species designated sensitive by the State occur nearby. Investigations are continuing as to the location of State protected and candidate threatened-or-endangered species.

Repository siting, construction, and operation may cause minor disturbances to wintering bald eagles when activities are centered around the Columbia River. This can be minimized by adjusting the seasonal time of activities. Raptors in the area may be caused to leave their nests, as may the long-billed curlew. Other animals in the area sensitive to noise and human intrusion will be displaced. The major impact will be the loss of habitat and the displacement or destruction of species through land disturbance, field studies, and construction. However, although the permanent loss of habitat is significant on the local scale, the area is not ecologically unique or sensitive. The regional habitat productivity is not likely to be affected.

A stretch of the Columbia River 4 miles south of the site is the only undammed segment of that river in the United States. The river is home to many birds and is a major spawning ground for the chinook salmon and the steelhead trout. No threatened or endangered species have been identified. Drilling near the river may disturb the bald eagle. As mentioned earlier, these effects can be minimized by drilling only during certain times of the year, or relocating drilling sites away from bald-eagle nesting sites.

Hanford is assigned a base-case score of 2.33. While considerable disruption or destruction of land and habitats is expected, there is no expected threat to threatened or endangered species or to the Columbia River.

Sensitive species (such as raptors) may be affected, but there is little likelihood of impacts on their regional abundance. An impact level of 3 includes some risk to threatened or endangered species. Since the risk is small in this case, Hanford is placed between 3 and 0.67, but closer to the upper end of the spread.

The low-impact score for Hanford is 1. Since most of the species in the area are common and nonsensitive, it is possible that the sensitive and threatened or endangered species would not be affected. The distance from the site to the Columbia River can serve as a protecting buffer for the river and its habitat. Impacts on nesting birds in the area can be minimized by limiting the time of disturbance to seasons during which the birds are not nesting or avoiding these areas to the extent practicable.

The high-impact score for Hanford is 3.5. If the ongoing flora studies reveal sensitive and threatened or endangered plant species on or near the site, then the potential for impacts on these species may be higher than expected for the base case. The lack of onsite nesting areas for threatened or endangered species indicates that no major critical habitats are likely to be found. It is possible, however, that more sensitive and threatened or endangered species may be located on the site and that in the event of impacts on the Columbia River, the spawning grounds for various fish may be affected. Therefore, at the worst, the score for Hanford is higher than 3. Although the likelihood of this is low, the potential consequences are high, and therefore the high-impact score for Hanford is 3.5.

Yucca Mountain

The Yucca Mountain site encompasses three floristic zones: the Mojave Desert, the Great Basin Desert, and a transition zone. The animals in the area are common, and no plants or animals at the site have Federal status as threatened or endangered species. The Mojave fishhook cactus and the desert tortoise, which occur in the study area, are candidates for the list of threatened and endangered species. The desert tortoise is protected by the State. The density of the desert tortoise in the project area is lower than in other parts of its range.

No permanent or major sources of seasonal free water, and hence no riparian habitats, exist at Yucca Mountain. The larger washes and drainages in the area tend to contain a distinct flora consisting of species found only in washes or most common in washes.

The major environmental impact of the repository would be the disturbance and destruction of habitats and indigenous wildlife. Depending on the extent of damage to the soil, hundreds of years may be required for a total recovery.

Yucca Mountain is assigned a base-case score of 2. Wildlife may be affected by the destruction of catch basins and by the noise generated by construction, operation, and traffic. The most prominent impact would be habitat loss and abandonment. Most of the impact, however, would be felt by resources common to the area. Construction would avoid the Mojave fishhook cactus and the desert tortoise wherever possible. The affected land itself, though sensitive, is not ecologically unusual and represents only a small percentage of the surrounding biota in the region.

The low-impact score for Yucca Mountain is 1. This level of impact would occur if the sensitive species in the area were not affected and all impacts were limited to common species. The high-impact score is 2.67. The land itself may be affected, and the resulting potential for disruption could be large. The other sensitive resources in the area are the aforementioned cacti and tortoises. Although significant effects could be experienced by both of these sensitive species, the likelihood of such effects is low.

F.3 SOCIOECONOMIC IMPACTS

One of the objectives is to minimize adverse socioeconomic impacts from the repository and waste transportation.

The performance measure for this objective is a constructed scale concerned with the impacts of the repository on the local communities, the infrastructure of those communities, the ability of people in those communities to pursue their lifestyles, and the indirect economic implications for persons in the local communities. The constructed scale consists of five levels (see Table 4-5). Level 0 is defined to correspond to essentially no adverse socioeconomic impacts, and higher levels designate a greater level of adverse impacts.

The base-case scores for the five sites are given below and are described in the text that follows. The range shows the low- and high-impact scores.

Site	Level of impact (range)
Davis Canyon	2 (1.33-3)
Deaf Smith	1.67 (1-3)
Richton Dome	2 (1-3)
Hanford	0.33 (0-0.67)
Yucca Mountain	0.67 (0.33-2)

Davis Canyon

Considerable in-migration is expected for Grand and San Juan Counties and for the three communities of Moab, Monticello, and Blanding. The population of Grand and San Juan Counties in 1980 was 20,494. By 1997, during peak construction, the baseline population in those counties is projected to increase to 24,030. The baseline population of Moab, including Spanish Valley, is projected to increase to 7464 by 1997. The baseline populations of Monticello and Blanding are projected to increase to 2433 and 3933, respectively, by the same year. Estimates of repository-related in-migration show a cumulative population increase of about 4690 persons over the first 6 years of construction. Moab is expected to receive 50 percent, or 2350, of these in-migrants, while Monticello and Blanding are projected to receive 1200 and 940 in-migrants at the peak, respectively. Major upgrading of the public infrastructure would be required. Impacts on area housing are expected to be major: the housing needed by repository-related households could reach 1600 units, but fewer than half this number of units are currently available in the study area. Additional personnel and equipment would be required in Moab, Monticello, and Blanding to meet increased demands for fire protection, police protection, health services, sewage treatment, social services, and solid-waste disposal. All communities are likely to need new landfills and additional classroom space. New streets and sewer and water lines would also be needed for the necessary new housing developments. Substantial social changes may result from the considerable population growth and the decrease in the percentage of the population native to Utah. Considerable conflict between current and new residents is expected.

Mining, trade, and government are the major employers in Grand and San Juan Counties. Mining has played an important role throughout the last decade, averaging about one-third of nonagricultural employment in the two counties. In recent years, mining employment has declined significantly, while employment in the government sector has increased. Total employment in the two counties in 1984 was 7240. Direct and indirect employment during repository operation is expected to peak at 2070. Such direct and indirect employment may result in the area's becoming economically dependent on the repository.

Land-use and land-ownership impacts are expected to be minimal. Minor impacts are expected on tourism and local recreation. If current plans to upgrade the water system in Moab and Monticello are completed, excess capacity should be available in all towns even after baseline needs are met; therefore, a diversion of water resources from other activities should not be needed. Only 4 percent of the land needed for repository construction and operation is privately owned, and no commercial or residential displacement is expected.

The base-case estimate for the Davis Canyon site corresponds to impact level 2 on the performance measure for socioeconomics. Although in-migration and economic dependence may be more severe than described for impact level 2, inadequacies in the public and private infrastructure are balanced by the greater compatibility of the repository with existing land use and ownership. Minor impacts are expected on the local tourism industry. No diversion of water resources is expected. Only 4 percent of the site is privately owned, and no displacement is expected. The lifestyles and values of the in-migrants, however, are expected to conflict with those of the current residents.

The low-impact score for Davis Canyon is 1.33. Although the affected communities do not have large population or employment bases, fewer lifestyle conflicts may occur than forecast because the area has a history of mining, and, because of the recent economic decline, local miners may be available. Impacts on existing land and resource uses may also be minimal because only 4 percent of the land is privately owned, and no displacement is expected. Impacts on tourism and local recreation are expected to be minor. Because in-migration cannot be expected to be small enough to cause only moderate impacts on the public infrastructure and housing, the low-impact score is not as low as 1. However, because the DOE believes that incompatibility between the lifestyles and values of newcomers and current residents or incompatibility with land use and ownership should be weighed more heavily than inadequacies in the public- and private-service structure, the low-impact score for the Davis Canyon site is close to a level described as 1 in Table 4-5 and is significantly better than the example scenario given for level 2.

The high-impact score for Davis Canyon is 3. Communities in the study area are small, and lifestyle conflicts between current and new residents could be extensive. Because of the site's proximity to the Canyonlands National Park and other tourist areas, unexpected and negative impacts may occur on primary land uses like those related to tourism and local recreation. In addition, the possibility that business patterns could be disrupted and economic decline could follow the completion of waste-emplacement operations cannot be dismissed, given the area's previous economic trends and the percentage of total employment due to the repository.

Deaf Smith

The 1980 population of the nine-county study area for the Deaf Smith site was 281,060 in 1980. By 1997, during peak construction, the baseline populations of the four major communities in the study area are expected to be as follows: Amarillo, 184,746; Hereford, 20,028; Canyon, 14,455; and Vega, 1215. Estimates of repository-related in-migration show a cumulative population increase of 2520 over the first 6 years of construction. Amarillo is expected to receive 60 percent, or 1510 of these in-migrants, while Hereford, Canyon, and Vega are expected to receive 630, 150, and 100 at the peak, respectively. This level of population increase is not expected to cause a significant disruption of public services. Impacts on public services are expected to occur mainly in Amarillo, Hereford, Canyon, and Vega. The additional public services--including schools, fire and police protection, water supply, and recreation--required by in-migration are expected to be minimal. The projected net change in total population within commuting distance of the site is less than 1 percent of the baseline population. A moderate increase in housing needs in the study area is expected. Although considerable in-migration is not expected, there could be some differences in lifestyles and values between current and new residents given the relatively stable farm-based population of the area.

Impacts on the existing agricultural land uses are expected to be minor. Although some temporary impacts on agriculture may result from the perception of consumers concerning a repository, these impacts should not be large or long lasting. In addition, the repository would place demands on the Ogallala aquifer. Although the demand from the repository is small in comparison with the current rate of use, the use of water from the Ogallala is a major problem for the entire region. All of the land is privately owned, and as many as 27 people may require relocation.

The economy of the affected area is moderately diverse. The primary sectors include retail trade (15 percent), government (18 percent), services (15 percent), agriculture (10 percent), and manufacturing (10 percent). Some of these employment sectors are closely related to or support regional agricultural activities. For example, in the manufacturing sector, the production of food and food products, agricultural chemicals and fertilizers, and farm equipment accounts for 40 to 45 percent of the sector.

Total employment in all sectors in the nine-county study area for 1980 was 137,365. Total employment in Deaf Smith County was 9669. Direct and indirect employment during repository operation is expected to peak at about 2300 workers. Given the employment base in the area, the area is not expected to become economically dependent on the repository.

The Deaf Smith site is assigned a base-case score of 1.67. All land is privately owned, with the displacement of agricultural land uses and as many as 27 people expected. In addition, the lifestyles and values of many in-migrants are not expected to match those of the farm-based population in the study area. For these reasons, the performance of the Deaf Smith site is not expected to be better than the scenario cited for level 1 in Table 4-5, but it is slightly better than level 2. Major impacts on public services or housing are not expected. Population growth rates are not expected to be high, and most of the in-migrants are expected to locate in Amarillo, which has the infrastructure to accommodate them.

The low-impact score for Deaf Smith is 1. Population growth rates are not expected to be high. The impacts on the public infrastructure or housing are expected to be moderate, and nearly 140,000 persons are employed in the study area. Lifestyle and value differences between in-migrants and current residents may be reduced if more than the expected 40 percent of workers and their families settle in Amarillo. In addition, minor land-use impacts and little displacement of residents are expected. The Deaf Smith site is not expected to perform better than the scenario given in Table 4-5 for level 1, however, because all of the land is privately owned and displacement cannot be completely avoided. In addition, the repository would place additional demands on the Ogallala aquifer, but it would use less water than that needed to irrigate an area the size of the repository.

The high-impact score for the Deaf Smith site is 3. More workers and their families than projected in the environmental assessment (DOE, 1986b) may choose to settle in the smaller communities near the site instead of in Amarillo. Vega's population is expected to be 1215 in 1997. A settlement pattern with more in-migrants settling in Vega, Hereford, and Canyon could cause considerable conflict between new and old residents, and it could result in the need for additional housing in these communities as well as a major upgrading of the public infrastructure. Impacts on agriculture could also be more severe than forecast in the environmental assessment. The site, however, is not assigned a high-impact score higher than 3. A substantial economic decline is not likely after the completion of waste-emplacement operations because of the large employment base in the region. Furthermore, many (even if not the projected 40 percent) in-migrants are likely to settle in the Amarillo area.

Richton Dome

At Richton Dome, the population in the study area is projected to be 247,650 persons in 1995. The baseline populations of the key communities in the study area are projected to be as follows at the time of peak construction: Hattiesburg, 46,240; Petal, 9580; Laurel, 24,750; and Richton, 1310. A total of about 2420 workers and their families are expected to move into the area during the first 4 years of repository construction, with 40 percent of the in-migrants expected to settle in Hattiesburg, 20 percent in the town of Richton (because of its proximity to the site), 15 percent in Laurel, and 10 percent in Petal. The expected level of in-migration would require a moderate increase in public services, including additional teachers, police officers, physicians, hospital beds, water and sewage treatment, and recreation space. Over 700 additional housing units may also be needed.

Conflicts in lifestyles between current residents and newcomers are expected, especially in the town of Richton, which is projected to receive 483 in-migrants, a 37-percent increase over baseline projections for the peak year of construction.

The economy in the region is moderately diverse. The primary sectors are manufacturing (21 percent), government (25 percent), and trade (22 percent). Total employment in the study area in 1981 was nearly 72,000. Employment in 1981 in Perry County was 1980. Direct and indirect employment during repository operation is expected to average over 1900 jobs; therefore, the area is not expected to become economically dependent on the repository.

Minor impacts on existing land use and ownership are expected. Since all the land is privately owned, residents at the site will be displaced. The specific location of the controlled area will determine the number of residents who must be relocated. Land requirements for the repository will result in the loss of 0.15 percent of the forestland in Perry County. No diversion of water resources from other uses is expected.

The base-case score for the Richton Dome site is equivalent to level 2 on the socioeconomic performance measure. Moderate in-migration is expected in the affected communities, and no major upgrading of public infrastructure or increases in housing will be needed. Some social conflict is expected between new and current residents, especially in Richton. Impacts on existing agricultural and commercial land uses are expected to be minor, and no diversion of water is expected. All the land is privately owned, and residential displacement is projected.

The low-impact score for Richton Dome is 1. Lifestyle and value differences between in-migrants and current residents may be minimal if more people settle in Hattiesburg than expected. Minor land-use displacement and minor displacement of residents are expected. Similarly, impacts on the public infrastructure or housing should be moderate. The impact level at the Richton Dome site, however, is unlikely to be lower than the example scenario given for level 1, because all the land is privately owned and because the town of Richton is so close to the site.

The high-impact score for Richton Dome is 3. Some workers and their families may choose to settle in the town of Richton because of its proximity to the site. Such a settlement pattern could cause increased conflicts between new and old residents, the need for major upgrading of the public infrastructure, and the need for additional housing. Depending on the specific location of the controlled area within the site, a large number of residences could be displaced. In addition, because of Perry County's low employment base, economic decline may follow the completion of waste-emplacement operations. Public infrastructure and housing supply in the town of Richton could also be affected since the population base is small.

Hanford site

In-migrants are expected to settle in the Richland-Kennewick-Pasco (Tri-Cities) metropolitan area. The population of Richland, Kennewick, and Pasco in 1984 was 31,660, 37,240, and 18,930, respectively. These three communities are 22 to 28 miles from the site. The population of Benton and

Franklin Counties in 1984 was 138,840. Considerable in-migration is not expected: the maximum increase in population over the base-line population is estimated to be 3900 persons. Public-service impacts are not expected in the Tri-Cities or in any of the smaller communities near the Hanford site. In-migrants moving into the region would find available services that were developed during the 1970s, when the area grew at a rapid rate because of several large construction projects. Because of significant employment and population losses in the area after 1981, excess capacity is expected to be available in housing, road networks, and other community services (e.g., health care, schools, police and fire protection, water supply, and sewer facilities). In addition, a highly skilled and young labor force has settled in the area during the last decade. Lifestyle and value conflicts between new and old residents are not expected.

The Tri-Cities area has many of the attributes of a regional trade center with a well-developed, complex economy. Total employment in the two counties in 1984 was 63,900. During the waste-emplacement phase of operation, the repository is expected to generate about 1800 direct and indirect jobs. The repository development is not expected to alter significantly the major sectors of the economy. For example, employment in agriculture and in other DOE projects at the Hanford Site depends on factors other than the repository. Growth in the agricultural and government sectors is expected to continue as a result of increased irrigation of farmlands and increased use of the Hanford Site for the production of nuclear materials and energy research.

Impacts on land use and land ownership are expected to be minimal because all of the land needed for the repository is owned by the Federal Government and controlled by the DOE. The Yakima Indian Nation, the Confederated Tribes of the Umatilla Indian Reservation, and the Nez Perce Indian Tribe, however, have been granted the status of affected Indian Tribes by the U.S. Department of the Interior because of the potential impacts on their off-reservation fishing rights. The predominant land use in the six-county region surrounding the Hanford site is agriculture. Radioactive materials have been managed at the Hanford site for the past 40 years with no apparent adverse impact on agricultural markets, even though there have been several well-publicized radioactivity releases to the environment.

No adverse impacts on water resources are expected. Municipal water systems in the study area are expected to be unaffected, because there is excess capacity in the Tri-Cities area where most in-migrants would live. In addition, the Federal Government already owns the water rights that are needed for a repository. Water would be supplied from the Columbia River.

The base-case score for Hanford is 0.33. The lifestyles and values of the small number of in-migrants are expected to be compatible with those of current residents. All land needed for the repository is owned by the Federal Government. Minor, if any, impacts on agricultural land uses are expected. Adverse impacts on public services, housing, and the area's economy are not expected.

The low-impact score for Hanford is 0.0. No agricultural impacts may occur in the counties surrounding the site, and no impacts on public services, housing, or the area's economy are expected. All land is federally owned, and the lifestyles and values of in-migrants are expected to be compatible with those of the current residents of the area.

The high-impact score for Hanford is 0.67. Two uncertain aspects of the socioeconomic forecast may result in a higher level of impact: (1) the extent and duration of the employment decline triggered by the termination of work on the nuclear reactor project of the Washington Public Power Supply System and (2) the sources and prospects for future economic recovery and growth in the region over the next three decades. If employment at the projects of the Washington Public Power Supply System or in other sectors of the economy increases substantially, then the current excess in community services and housing may disappear and the repository may contribute to a need to build additional housing and to expand the public-service infrastructure.

Yucca Mountain

Eighty-five percent of the in-migrating population is expected to settle in the metropolitan Las Vegas area of Clark County. The populations of Clark and Nye Counties are projected to be 661,700 and 34,790, respectively, in 1990. Estimates of repository-related in-migration show a maximum population increase in 1998 of 16,791. The estimated baseline population of Nye and Clark Counties for the same year without the project is 884,639. Sufficient infrastructure exists to accommodate in-migrants who settle in the Las Vegas area. In the rural communities closer to the Yucca Mountain site, public-service demands are expected to be moderate and to fall mainly on the service providers best equipped for dealing with growth (i.e., county-wide agencies with broad tax bases, planning capabilities, and experience in responding to population growth). Sufficient housing is expected to be available in Clark County to accommodate the in-migrants. Moderate increases in housing are expected for Nye County.

Since most in-migrants are expected to settle in the metropolitan Las Vegas area, the effects on social structure and organization are expected to be minor. In-migrants who settle in Nye County are also expected to be assimilated within the existing social structure, because communities in Nye County have historically had a large percentage of miners and mining continues to be important to the area.

The economy of Nye and Clark Counties is diverse enough to accommodate growth without major disruption to existing business patterns and without becoming overly dependent on the repository. Total wage and salary employment in Nye County in 1983 was 8630. Clark County's total wage and salary employment in 1980 was over 200,000. Direct and indirect employment during repository operation is expected to average about 4260. The primary sectors of the economy in southern Nevada are tourism and mining. The tourism economy is very diverse. Regarding mining, the repository would provide some additional jobs for miners in Nye County.

Land-use and land-ownership impacts are also expected to be minimal. All of the land needed for repository construction and operation is owned by the Federal Government. In addition, preliminary results of an on-going evaluation of the effects of a repository on tourism in southern Nevada have not identified significant negative impacts. Existing water rights and uses are not expected to be affected.

The base-case score for the Yucca Mountain site is 0.67. Lifestyle and value differences between in-migrants and the current residents of Nye and

Clark Counties are expected to be minimal. No land-use or land-ownership incompatibilities are expected. Minimal upgrading of public services and housing may be required in Nye County communities near the site.

The low-impact score for the Yucca Mountain site is 0.33. Although the expected settlement patterns may minimize public-service and housing impacts on communities in Nye County, it is not likely that all in-migrants will settle in Las Vegas, which is 95 miles from the site. Minimum public-service impacts can be expected even under the best scenario.

The high-impact score for the Yucca Mountain site is 2. A settlement pattern different from the projected one could result in major impacts on public services and housing in several small communities in Nye County. In addition, this growth could cause a minor diversion of water resources from other activities. At the same time, the tourism industry in Las Vegas could be affected more than preliminary studies indicate. The Yucca Mountain site, however, is not assigned a high-impact score higher than 2 because none of the land is privately owned and because the lifestyles and values of in-migrants are expected to be assimilated into the existing social structure of Nye and Clark Counties.

F.4 ECONOMIC IMPACTS

This section describes the bases for the costs estimated for the repository and waste-transportation operations. Costs are reported in constant 1985 dollars. The costs associated with gaining access to the site (e.g., by building new roads or railroads) are included in the estimates of total repository costs, not as part of the transportation costs.

F.4.1 TOTAL REPOSITORY COSTS

The total cost of the repository consists of four major components: development and evaluation (D&E), construction, operation, and closure and decommissioning. The development-and-evaluation category consists of all activities that are conducted before repository operation, excluding final design and construction. The construction category includes the final design and the construction of all surface facilities as well as the excavation of a limited number of underground waste-disposal rooms and corridors. The operation category covers the construction of most of the underground rooms and corridors and the operation of the surface and underground facilities. The last category, closure and decommissioning, covers the sealing of shafts and boreholes as well as the decontamination and decommissioning of the surface facilities.

The estimated costs for a repository at each of the five sites are shown in Table F-12. The basis for these estimates is the current report on the total-system life-cycle costs (Weston, 1986). These estimates were developed as part of the DOE's annual evaluation of the adequacy of the fee paid by the electric utility companies into the Nuclear Waste Fund and do not represent final cost estimates.

Table F-12. Repository-cost estimates
(Billions of 1985 dollars)

Cost category	Davis Canyon	Deaf Smith	Richton	Hanford	Yucca Mountain
Development and evaluation	1.6	1.6	1.6	1.6	1.5
Construction					
Surface	1.7	1.2	1.2	0.9	0.8
Underground	0.8	0.8	0.7	1.3	0.4
Subtotal	2.5	2.0	1.9	2.2	1.2
Operation					
Surface	3.1	2.7	2.6	3.6	3.0
Underground	1.9	2.0	1.7	4.0	1.2
Waste package	1.0	1.0	1.0	1.3	0.5
Subtotal	6.0	5.7	5.3	8.9	4.7
Closure and decommissioning					
Surface	0.2	0.1	0.1	0.1	0.1
Underground	0.1	0.1	0.1	0.1	0.0
Subtotal	0.3	0.2	0.2	0.2	0.1
Total					
Development and evaluation	1.6	1.6	1.6	1.6	1.5
Surface	5.0	4.0	3.9	4.6	3.9
Underground	2.8	2.9	2.5	5.4	1.6
Waste package	1.0	1.0	1.0	1.3	0.5
Total	10.4	9.5	9.0	12.9	7.5
Uncertainty band					
-35%	6.8	6.2	5.9	8.4	4.9
+35%	14.0	12.8	12.2	17.4	10.1

The cost estimates presented here are different from those found in Sections 6.3.4 and 7.3 of the environmental assessments for the nominated sites (DOE, 1986a-e). The estimates for the Yucca Mountain and the Hanford sites have been updated since costs were submitted for the environmental assessments. In addition, site-specific estimates for the salt sites were developed. The estimate for the Deaf Smith site is the estimate used in the 1986 fee evaluation, whereas the estimates for Davis Canyon and Richton Dome were generated specially for this report. All of the estimates fall within the design bounds established in Table 5-1 of the environmental assessments. More-definitive estimates will be completed when more-detailed designs and site-characterization data become available.

The uncertainty (reflected in the range shown in Table F-12) that has been assigned to these estimates is based on engineering judgment and is 35 percent of the total cost. This, coupled with a 10- to 40-percent contingency already built into the estimates, reflects the accuracy of the preconceptual design work from which the costs were derived. The exact contingency used depends on the complexity of the design of specific repository facilities or processes. For example, the waste-handling building, because of its complexity, is assigned a 40-percent contingency, while some of the site-preparation costs are assigned a contingency as low as 10 percent.

As can be seen from Table F-12, the D&E and decommissioning costs are not strongly discriminating among the nominated sites. The major discriminators are the costs of construction and operation, for both surface and underground facilities.

Construction costs account for about 20 percent of the total repository costs. Listed below are the four major factors that control construction-cost differences among sites. As indicated, three of them pertain to surface facilities and one is related to underground facilities.

1. Waste-handling facilities (surface). These facilities differ because of different waste-package designs and quantities, which are in turn greatly dependent on underground conditions.

2. Site access (surface). Costs vary widely because of differences in land ownership as well as the location of the site with respect to railroad, highway, and utility access.

3. Underground facilities (underground). The major differences in construction costs for underground facilities are attributable to shafts (the number of shafts, the method of construction, etc.). Shaft-construction costs are greatly influenced by depth, rock conditions, and ground-water conditions. (Most underground development, however, occurs during operation, and the cost of it is assigned to the operation-cost category.)

4. Ventilation requirements (surface). Because of differences in underground conditions, the three types of host rock require greatly different surface-support facilities for the underground operations. These may include shaft structures, ventilation and filter buildings, as well as refrigeration facilities.

The most significant cost discriminator among sites is the cost of operation. Since operation costs account for about three-fourths of the total repository costs, operation-cost differences control the total cost differences. The major factors that affect operation costs are the following:

1. Underground facilities. The costs of excavation are widely different for each site. They depend on the quantity of rock excavated, the mining method, and the mining rate. These in turn are based on the ease of mining and waste logistics. The former depends on host-rock depth, rock conditions and tunnel stability, ground-water conditions, and assumptions about the presence of gassy conditions.

2. Backfilling (both underground and surface). The requirements for backfilling underground facilities vary greatly among host-rock types, and these differences cause the operating period to differ widely. Both underground- and surface-support costs are affected by the length of the operating period.

3. Labor (both underground and surface). Labor costs exert a major effect on operation costs. They depend on both staffing requirements and local labor rates.

4. Waste packages. Waste-package costs vary widely between host-rock types. They depend on waste-package designs and quantities, which in turn depend on underground conditions and rock characteristics, such as the thermal conductivity of the host rock.

The major factors that control construction and operation costs are listed in Table F-13 and are briefly described below. For the sake of brevity, the discussion is organized by discriminating factor, not by site. The influence diagram for repository costs (Figure E-13 in Appendix E) will also help the reader in identifying important factors and their interrelationships. For a detailed description of the methods and assumptions used in developing the information presented in Table F-13, the reader is referred to the current report on total-system costs (DOE, 1986).

Discriminating factor 1 illustrates the land-acquisition and site-access cost differences among the nominated sites. These differences are caused by differences in land ownership and site location. Davis Canyon has the highest site costs because rail and highway construction requires 1.5 miles of bridges and 9.0 miles of tunnels, and long utility lines are required. Yucca Mountain has the next highest cost because a 103-mile railroad and highway must be constructed. Deaf Smith and Richton Dome have lower access costs but require land-acquisition costs because they are not on Federal land. The Hanford site, which has good access and is on Federal land controlled by the DOE, has no land-acquisition costs and low site-access costs.

Discriminating factor 2 is the size of the waste-handling facilities. At Yucca Mountain, the facilities are considerably smaller (and in turn less costly) than those of the salt sites or Hanford. The designs are site specific and are affected by the number, the size, and the type of waste package, as discussed below for factor 17.

Discriminating factors 3, 4, 5, and 10 describe the underground-access differences that affect costs. The numbers of shafts and ramps (including exploratory shafts) vary from 6 at Yucca Mountain to 11 at Hanford, with 7 at each salt site. The differences are attributable to different underground requirements (ventilation, men and material transfer, etc.) and limitations on shaft sizes. Discriminating factor 4 shows that shafts at all the salt sites as well as Hanford must have hydrostatic liners because they must penetrate water-bearing strata, and the costs of liners are a significant portion of the shaft costs. The construction techniques vary from drilling at Hanford to conventional mining at the other sites. Two of the salt sites, Deaf Smith and Richton, incur extra costs for ground freezing while sinking the shafts through water-bearing strata. An important factor is depth (factor 10), which ranges from 1200 feet at Yucca Mountain to 3300 feet at Hanford. These factors combine to produce a tenfold difference in shaft costs among the sites. Hanford has the highest shaft costs, because it has the largest number of shafts, requires hydrostatic liners, and the shafts are deeper than those at other sites. Yucca Mountain has the lowest underground-access costs because it uses ramps instead of some shafts, it has the smallest number of shafts, the repository horizon is less deep than that at other sites, and no

Table F-13. Major factors controlling differences in construction and operation costs among nominated sites

Factor	Davis Canyon	Deaf Smith	Richton Dome	Hanford	Yucca Mountain
1. Land acquisition and site access (billions of dollars)	0.9	0.3	0.3	0.1	0.4
2. Size of waste-handling buildings (millions of cubic feet)	21.0	21.0	21.0	20.4	13.0
3. Total number of shafts or ramps required for underground access (includes exploratory shafts)	7 shafts	7 shafts	7 shafts	11 shafts	4 shafts and 2 ramps
4. Need for hydrostatic lining for shafts or ramps	Yes	Yes	Yes	Yes	No
5. Method of sinking shafts or ramps	Conventional	Conventional, extensive freezing	Conventional, moderate freezing	Drilling	Conventional
6. Number of shaft buildings required for ventilation	4	4	4	6	3
7. Gassy-mine conditions	Assumed	Assumed	Assumed	Not present	Not present
8. Excavation quantity (millions of tons)					
Initial	27	27	26.5	13	18
Reexcavation	1	6	2.5	0	0
Total	28	33	29	13	18
9. Excavation method	Mechanized	Mechanized	Mechanized	Conventional	Conventional and mechanized
10. Depth (feet)	3000	2700	2100	3300	1200
11. In-situ temperature (°C (°F))	34-43 (93-109)	27 (81)	50 (122)	51 (124)	27 (81)
12. Potential ground-water inflow to repository (thousands of gallons per minute)	0.028	1.4	1.7	3.4	None
13. Labor productivity (tons per man-shift)	17.1	15.0	15.9	5.0	13.0

Table F-13. Major factors controlling differences in construction and operation costs among nominated sites (continued)

Factor	Davis Canyon	Deaf Smith	Richton Dome	Hanford	Yucca Mountain
14. Backfilling duration (years)	3[B]	3[B]	3[B]	34	0
15. Staffing levels (full-time equivalents)[C,D]					
Surface operations	830	830	830	1062	872
Underground operations	413	460	434	596	285
Total	1243	1290	1264	1658	1157
16. Underground labor rate (dollars per man-hour)[E]	24.30	22.84	20.00	30.75	32.00
17. Waste packages					
Number required for spent fuel	16,500	16,500	16,500	37,000	27,400
Material	Thick-walled carbon steel	Thick-walled carbon steel	Thick-walled carbon steel	Thick-walled carbon steel	Thin-walled stainless steel
Need for internal canister	Yes	Yes	Yes	No	No
Total fabrication costs (billions of dollars)	1.0	1.0	1.0	1.3[F]	0.5

[A] Source of ground water could be leakage through and around shaft liners or leakage from working faces; for the salt sites, brine pockets could be sources. For comparison, ground-water inflows of 20,000 gallons per minute are routinely managed in the mining industry, depending somewhat on depth, temperature, and other conditions.

[B] In a salt repository the backfilling of disposal rooms would be conducted throughout the operating period.

[C] Staffing levels cover the waste-emplacement phase only.

[D] See Section F.1.3 for a detailed discussion of staffing levels.

[E] Surface-labor rates follow the same trend as underground-labor rates.

[F] Includes the cost of the bentonite-and-basalt packing component.

hydrostatic liners are needed. The costs of shafts for Davis Canyon and Deaf Smith are nearly identical because of offsetting design discriminators (depth versus freezing), while the costs of shafts for Richton Dome are the lowest of the salt sites.

Discriminating factor 6 indicates differences in surface ventilation structures, which vary from three buildings at Yucca Mountain to six at Hanford and are reflective of underground conditions. Discriminating factor 7 shows that all of the salt sites are assumed to have gassy mine conditions, while the others are not. This results in the salt sites having the highest ventilation costs. The Hanford ventilation systems must handle the warmest, most humid air, while the Yucca Mountain systems handle cool, relatively dry air (see discriminating factors 11 and 12).

Discriminating factors 7 through 13 illustrate large differences in underground development, which lead to large differences in both construction and operation costs. The amount of excavation varies for each site, as shown by factor 8. The differences are due to a combination of underground conditions, including factors 10, 3, and 7 from Table F-13. The greatest quantity of excavation is required at the salt sites because of the assumed gassy-mine conditions and salt creep. The continuous creep of salt requires the reexcavation of open drifts to maintain waste-emplacement operations. The creep rate and thus the quantity of reexcavation varies among the salt sites, with the Deaf Smith site having the highest rate of creep and excavation. The Hanford site has the lowest quantity of excavation, while Yucca Mountain is between Hanford and the salt sites.

Although the salt sites have the highest excavation quantities, their underground-development costs fall between those of Yucca Mountain (lowest) and Hanford (highest). The underground-development costs are the product of the excavation quantities and unit development costs. These unit costs are determined by site-specific underground conditions, such as rock hardness, rock stability, temperature, and ground-water inflow (discriminating factors 9 through 13 in Table F-13). These conditions dictate both excavation methods and mining rates.

The salt sites have the lowest unit development costs because they have the highest productivity (mining rates). At these sites, rock conditions permit the use of mechanized techniques rather than conventional methods, and the requirements for roof support are minimal (Davis Canyon and Richton) to moderate (Deaf Smith). The in-situ temperatures are low at Davis Canyon and Deaf Smith, but somewhat higher for Richton. The air at all sites is relatively dry. Finally, minimal quantities of ground water are expected at the repository horizons.

The Hanford site has the highest unit development costs because it has the lowest productivity. The basalt at Hanford is a hard rock that requires the use of conventional mining methods, moderate roof support is needed because of rock conditions, the in-situ temperature is high, the air is very humid, and the ground-water inflow is expected to be high.

The unit development costs for Yucca Mountain are higher than those for the salt sites but considerably lower than those for Hanford. Because tuff is a hard rock, most of the mining would be done by conventional methods, but some mechanized boring is considered. Minimal roof support is required because of favorable rocks conditions. The in-situ temperature is low, and the air is dry. In addition, the repository is located above the water table, and hence no ground-water inflow is expected.

Backfill requirements for the underground excavations vary considerably among sites and lead to large operating-cost differences. Discriminating factor 14 shows the length of the backfill period. No backfill is planned for the Yucca Mountain repository, and hence no backfill cost is incurred. The salt sites have a 3-year backfill period after the caretaker phase, but the disposal rooms are backfilled throughout the waste-emplacement period (starting 1 year after emplacement), which minimizes salt handling and surface storage. By far the highest cost for backfill is included in the estimate for the Hanford site, which has a 34-year backfill period after the caretaker phase as opposed to 3 years for salt.

Discriminating factors 15 and 16 illustrate site differences in labor costs, which account for most of the operation costs. Discriminating factor 15 shows the emplacement-phase staffing levels for each site, while factor 16 shows the site-specific labor costs. Staffing levels are highest for Hanford and lowest for Yucca Mountain. The staffing estimates depend on surface and underground operations, while the labor rates reflect regional cost trends and local labor contracts in place at the Hanford and the Yucca Mountain sites. Staffing (and operating costs) to a large degree reflect differences in repository design. Thus, in addition to engineering judgment on the part of the designer, the repository design (see discriminating factors 2, 3, and 5 through 9) affects staffing levels.

The last discriminating factor in Table F-13 shows waste-package design and cost differences for each site. Differences in waste-package costs are due to great differences in waste-package design, which depends on rock characteristics, stresses, the chemical waste-emplacement environment, and performance requirements. The numbers of waste packages for spent fuel are based on site-specific heat loadings, which are constrained by the thermal and physical characteristics of the host rock. The waste packages therefore use different components and materials. For example, the waste packages for Hanford and the salt sites have thick-walled disposal containers made of carbon steel. At Hanford, the disposal container is surrounded by external packing (bentonite and crushed basalt) in the waste-emplacement hole, and special packing assemblies are added to the container before it is transferred underground. At the salt sites, the package for spent fuel includes an internal metal canister for the spent-fuel rods. The package for Yucca Mountain is encapsulated in a thin-walled stainless-steel disposal container. The differences in quantities, materials, and components yields waste-package costs that vary from a low of $0.5 billion (Yucca Mountain) to a high of $1.3 billion for Hanford.

The repository-cost estimates used in the preclosure analysis are based on a constant cost of money--that is, constant 1985 dollars--throughout the life cycle of the repository, including activities like backfilling, decommissioning, and closure, which may not take place for decades. The DOE, therefore, performed a present-value analysis of the repository cost-estimates by discounting the cost in order to identify the sensitivity of the estimates to the time value of money. Using a 3-percent discount rate as an example,

Table F-14 shows that the cost estimate for each site, especially the Hanford site, is sensitive to the time value of money. In this example, the cost ranking of the sites remains the same; however, the cost difference between the sites is reduced, especially between the Davis Canyon and the Hanford sites.

Table F-14. Present-value analysis of the total repository costs[a]
(Millions of dollars)

Site	Constant cost ($1985)	Cost ranking	Discounted cost (at 3%)	Cost ranking
Yucca Mountain	7,500	1	4255	1
Richton Dome	8,659	2	4948	2
Deaf Smith County	9,584	3	5395	3
Davis Canyon	10,428	4	5919	4
Hanford	12,930	5	6334	5

[a] Includes the costs of development and evaluation, construction, operation, decommissioning, and closure.

F.4.2 TRANSPORTATION COSTS

The last of the objectives defined for this analysis is to minimize the costs of transporting waste from the sources to each site. The analysis uses a logistics code, WASTES, that analyzes the cost of transportation and hardware requirements (Shay et al., 1985). The hardware costs, both maintenance and capital, are evaluated by using the output from WASTES. The total costs therefore consist of three components:

1. Shipping costs, which are based on published tariffs and could change, depending on negotiations with carriers.

2. Capital costs, which include the costs of the shipping casks and the costs of the trailer or railcar. The number of casks required depends on the distance of travel. The number of casks required for each site is summarized in Appendix A of the environmental assessments (DOE, 1986a-e).

3. Maintenance costs, which are based on an assumed 15-year life of the cask.

All three factors are highly dependent on the assumptions underlying the analysis, as briefly described below.

In calculating costs, the spent-fuel discharge data published in a recent DOE report (Heeb et al., 1985) were used. In all scenarios a total of 62,000 MTHM of spent fuel was shipped from the reactor sites. The amount of spent fuel shipped from each reactor site was selected on a yearly basis by applying the following criteria:

1. Reactors without a full-core-reserve capacity in a given year were given highest priority.

2. Reactors undergoing decommissioning were given the next highest priority 2 years after the last year of their operation.

3. The oldest fuel remaining at reactors was given final priority.

The other assumptions used in this analysis are given in Cashwell et al. (1985).

The WASTES model was used to calculate shipping costs and the size of the cask fleet. This model has considered past work in its development and has been benchmarked against past analyses. A good discussion of its capabilities is presented by Shay et al. (1985).

The costs of transporting waste to the various sites are shown below. The truck-to-rail ratio is assumed to be 30 to 70 as described in Section F.1.5. The ranges account for the uncertainty associated with the second repository (+40 and -46 percent) and the uncertainty associated with models and data (+50 and -50 percent).

Site	Total transportation costs (range) (billions of 1985 dollars)
Davis Canyon	1.2 (0.33-2.6)
Deaf Smith	1.12 (0.30-2.4)
Richton	0.97 (0.26-2.04)
Hanford	1.45 (0.39-3.04)
Yucca Mountain	1.4 (0.38-2.94)

As with the other transportation-related performance measures, there is a direct correlation between distance and transportation costs. The correlation is not linear, however, because the costs include costs for loading and unloading (as part of shipping costs), which are unaffected by distance. The result is that a shipment between points 1000 miles apart does not cost twice as much as a shipment between points 500 miles apart; the cost is likely to be considerably less than double.

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Appendix G

THE MULTIATTRIBUTE UTILITY FUNCTION FOR EVALUATING NOMINATED SITES

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THE MULTIATTRIBUTE UTILITY FUNCTION FOR EVALUATING NOMINATED SITES*

To evaluate the five sites nominated as suitable for site characterization, 16 objectives were defined. Fourteen of these objectives pertain to preclosure, and the other two objectives pertain to postclosure. The preclosure objectives concern the possible consequences of a repository in terms of health and safety impacts, environmental impacts, socioeconomic impacts, and economic cost impacts. The postclosure objectives both concern health and safety impacts.

Whenever multiple objectives are necessary to evaluate alternatives, value judgments must be made about the relative importance of different consequences with respect to different objectives. The analysis in this report makes these assessments and their implications explicit. The result of these assessments is an objective function for evaluating the alternatives. Such an objective function is referred to as a "multiattribute utility function."

The purpose of this appendix is to clarify all aspects of the objective function used in the analysis. Specifically, the appendix explains what was done to assess the multiattribute utility function, why and how this was done, and the implications and appropriateness of the resulting multiattribute utility function. The intent is to assist readers in understanding and appraising the evaluation process.

Overview of the assessment process

The explicit assessment of a multiattribute utility function is essentially building a model of the value structure appropriate for evaluating alternatives. The general process is identical with that necessary to develop any analytical model, such as models of ground-water flow, of traffic accidents, of meteorological dispersion of materials, or the health effects induced by exposure to various substances. The first step is to postulate a potentially reasonable model that combines the variables felt to be important to describe the relationship of interest. The reasonableness of the assumptions necessary for the postulated model is then examined. Given that the assumptions are found to be reasonable, the general form of the model (i.e., an equation) is fixed. However, there is often a number of parameters which need to be specified to render the model appropriate for the specific purpose under consideration. With a model of ground-water flow, such parameters may be levels of such variables as porosity, temperature, pressure, and tortuosity. With the value model, parameters refer to the relative

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importance of specific changes in levels of different consequences and to attitudes toward risk. With physical models, data to specify parameters are often determined from scientific experiments (e.g., drilling holes to measure the variables affecting ground-water flow). With value models, the data necessary to specify parameters in a model are the value judgments gathered from individuals with responsibilities for recommending or making the decision under consideration. With both physical models and value models, the model should be examined for consistency and logic in as many situations as the problem affords that are felt to be worthwhile. In either case, this review process may lead to necessary revisions. The resulting models are then ready to be of assistance in evaluating the alternatives.

Outline of the appendix

The appendix has five sections. Section G.1 briefly outlines the theoretical foundations of multiattribute utility theory and the procedures used to implement it. Section G.2 presents all of the assessments used to specify the multiattribute utility function. This function, and its implications, are discussed in Section G.3. Section G.4 presents the reasons that the multiattribute utility function is appropriate for evaluating alternative nuclear repository sites. Section G.5 discusses the consistency of the utility function with the guidelines.

G.1 FOUNDATIONS OF THE APPROACH

The approach used to develop an objective function for evaluating the nominated sites rests on sound theoretical and logical foundations. In addition, numerous procedures have been developed over the last 20 years to implement the theory in a manner that is consistent with these foundations. This section provides a brief summary of the key ideas of the theory and procedures. The intent is to introduce the reader to the theory and to provide references for further investigation.

To facilitate communication, it is useful to define precisely the problem being addressed in terms of the notation used throughout this appendix. There are five sites to be evaluated as a potential repository site. The sites will be evaluated in terms of 16 objectives measured by a set of performance measures X_i ($i = 1,...,16$). Fourteen of these objectives are used to describe preclosure consequences, and two are used to describe postclosure consequences. A specific consequence with respect to performance measure X_i is denoted x_i ($i = 1,...,16$). Thus, a consequence $x = (x_1,...,x_{16})$ can be used to describe a consequence that might result from a repository at the site.

The theory may seem less abstract with some examples. One of the objectives is to minimize the health effects incurred by workers from radiation exposures at the repository site; the performance measure for this objective is the number of latent-cancer fatalities induced by radiation at the site. Another objective is to minimize repository costs, and the associated performance measure is cost in millions of dollars. A consequence with respect to this performance measure may be 6,300, meaning the repository cost is 6,300 million dollars (i.e., 6.3 billion dollars).

G.1.1 UTILITY THEORY

There are different types of objective functions that can be used to develop a model of values. The basic property of all objective functions involving multiple performance measures is to assign a number to each consequence, such that consequences that are preferred have a higher number and that higher numbers assigned by the objective function indicate preferred consequences. More precisely, an objective function v assigns a real number v(x) to each consequence, such that x is preferred to x' if and only if $v(x) > v(x')$ and x is indifferent to x' if and only if $v(x) = v(x')$. Thus, the objective function can provide a ranking of the consequences.

A multiattribute utility function, denoted by u, is a special type of objective function. In addition to assigning higher numbers to preferred consequences, it provides a means of obtaining a ranking for lotteries over consequences. These lotteries are necessary to describe situations involving uncertainty; specifically, they indicate a series of possible consequences and the probability that each will occur. The utility function u assigns a real number u(x) to each consequence such that a lottery L_1 should be preferred to a lottery L_2 if and only if the expected utility of lottery L_1 is greater than the expected utility of lottery L_2, and L_1 should be indifferent to L_2 if and only if their expected utilities are equal. The utility function follows from a set of fundamental axioms expressed in different ways by von Neumann and Morgenstern (1947), Savage (1954), and Pratt, Raiffa, and Schlaifer (1964).

Another type of objective function is the measurable-value function, denoted by w. In addition to assigning higher numbers to preferred consequences, the measurable-value function provides a ranking of the differences in value between pairs of consequences. Specifically, the measurable-value function assigns a real number w(x) to each consequence such that the significance of changing from consequence x to x' is greater than changing from consequence y to y' if and only if $w(x') - w(x) > w(y') - w(y)$ and is the same if and only if $w(x') - w(x) = w(y') - w(y)$, where x' and y' are respectively preferred to x and y. With a measurable-value function, the differences in w values do have an interpretation, but the expectation of w has no meaning, which is just the reverse of the case with the utility functions. The foundations of measurable-value theory can be found in numerous sources, including Debreu (1960), Luce and Tukey (1964), Krantz et al. (1971), and Dyer and Sarin (1979).

In addition to being a multiattribute utility function, the utility function used for evaluating sites in this study was shown to be a measurable-value function. Hence, it can be used to evaluate possible consequences described by lotteries, and the results can be used to indicate the strength of preferences for different alternatives using the measurable-value property.

G.1.2 INDEPENDENCE ASSUMPTIONS

The main concepts of multiattribute utility theory concern independence conditions. Subject to a variety of these conditions, the assessment of u can be divided into parts, each much easier to tackle than the whole.

It is desirable to find simple functions f, $u_1,\ldots,u_n$ such that

$$u(x_1,\ldots,x_n) = f[u_1(x_1),\ldots,u_n(x_n)], \qquad \text{(G-1)}$$

where x_i is a level of attribute X_i and there are n attributes, which is the general term of utility theory analogous to the more specific term of performance measure used in the repository-siting analysis. Then the assessment of u is reduced to the assessment of f and u_i ($i = 1,\ldots,n$). The u_i are single-attribute functions, whereas u and f are n-attribute functions. If f is simple, such as additive, then the assessment of u is simplified. The independence concepts discussed below imply the simple forms of f indicated later in this section.

Four main independence conditions are relevant to building multiple-objective value models: preferential independence, weak-difference independence, utility independence, and additive independence. In the discussion that follows all four are stated, briefly discussed, and then contrasted.

Preferential independence. The pair of attributes (X_1,X_2) is preferentially independent of other attributes $X_3,\ldots,X_n$ if the preference order for consequences involving only changes in the levels of X_1 and X_2 does not depend on the levels at which attributes $X_3,\ldots,X_n$ are fixed.

Preferential independence implies that the indifference curves over X_1 and X_2 do not depend on other attributes. This independence condition involves preferences for consequences differing in terms of two attributes, with no uncertainty involved.

The next assumption is also concerned with consequences when no uncertainty is involved. However, it addresses the strength of preferences (i.e., value differences) when changes occur in only one attribute.

Weak-difference independence. Attribute X_1 is weak-difference independent of attributes $X_2,\ldots,X_n$ if the order of preference differences between pairs of X_1 levels does not depend on the levels at which attributes $X_2,\ldots,X_n$ are fixed.

There are two important assumptions relating to situations that do involve uncertainty. As such, the conditions use preferences for lotteries rather than consequences. A lottery is defined by specifying a mutually exclusive and collectively exhaustive set of possible consequences and the probabilities associated with the occurrence of each.

Utility independence. Attribute X_1 is utility independent of attributes $X_2,\ldots,X_n$ if the preference order for lotteries involving only changes in the level of X_1 does not depend on the levels at which attributes $X_2,\ldots,X_n$ are fixed.

The last independence condition concerns lotteries over more than one attribute.

<u>Additive independence</u>. Attributes $X_1,...,X_n$ are additive independent if the preference order for lotteries does not depend on the joint probability distributions of these lotteries, but depends only on their marginal probability distributions.

To get an intuitive feeling for these assumptions, let us illustrate them in simple cases. The substance of preferential independence can be indicated with a three-attribute consequence space as shown in Figure G-1.

To avoid subscripts, the attributes are denoted X, Y, and Z with corresponding levels x, y, and z. There are three X, Y planes shown in the figure. By definition, if (X,Y) is preferentially independent of Z, then the preference order for consequences in each of these planes (and indeed in all possible X, Y planes) will not depend on the level of Z. For instance, suppose the consequences in the plane with Z set at z° can be ordered A, B, C, D, E, F, G, with H indifferent to G. Then, because of preferential independence, the consequences in the plane with Z set at z' must be A', B', C', D', E', F', G', with H' indifferent to G'. And also, with Z set at z*, the order must be A*, B*, C*, D*, E*, F*, G*, with H* indifferent to G*.

An implication of preferential independence is that the indifference curves in all X, Y planes must be the same. Several indifference curves are illustrated in each of the three planes in Figure G-1, and it is easy to see that they are the same.

The usefulness of preferential independence is that it allows one to determine the preference order for consequences in only one X, Y plane and to transfer this to all other planes. If (X,Y) is preferentially independent of Z, it does not follow that any other pairs are preferentially independent. However, for any number of attributes, if two pairs of attributes overlap and are each preferentially independent, then, as proved by Gorman (1968a,b), the pair of attributes involved in only one of the two given conditions (i.e., not in the overlap) must also be preferentially independent. This means, for our example, that if (X,Y) is preferentially independent of Z and (X,Z) is preferentially independent of Y, then (Y,Z) must be preferentially independent of X.

The next two independence assumptions can be illustrated most easily with two attributes, as shown in Figure G-2. Here the attributes are X and Y with levels x and y. Weak-difference independence introduces the notion of difference in value between two consequences. The purpose is to provide the logical basis for such statements as "the difference between consequences A and B is more important than the difference between consequences C and D." Weak-difference independence is illustrated in Figure G-2 as follows. Suppose that, through a series of questions, it has been established that the preference difference between consequences A and B is equal to the preference difference between B and C. Because the level of Y is fixed at y° for all three of these consequences, the preference-difference relationship can be translated to all other levels of Y if X is weak-difference independent of Y. In this case, the preference difference between A' and B' must equal that between B' and C', and the preference difference between A* and B* must equal that between B* and C*. With this condition there is, however, no requirement that the preference difference between A and B be equal to that between A' and B', although this may be the case.

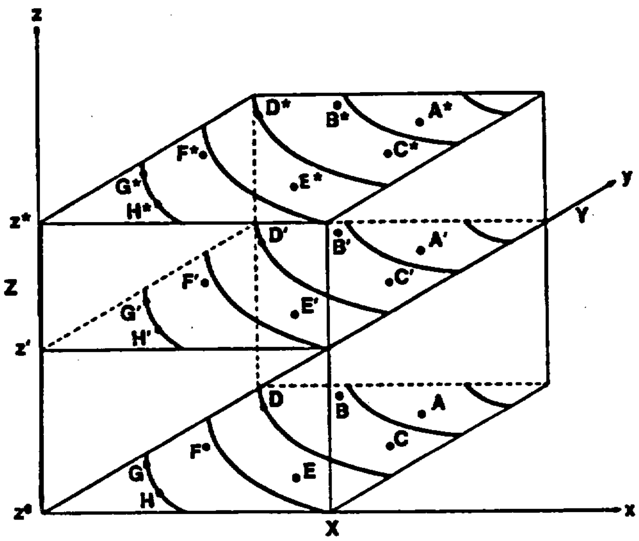

Figure G-1. Illustration of preferential independence.

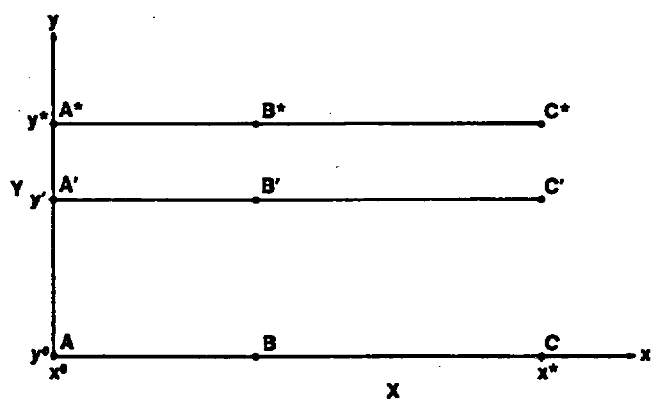

Figure G-2. Illustration of value-difference independence and utility independence.

Weak-difference independence is not a symmetrical relationship. That is, the fact that X is weak-difference independent of Y does not imply anything about whether Y is weak-difference independent of X. In terms of the example, suppose y' had been chosen such that the preference difference between A and A' equaled that between A' and A*. Then, even if X is weak-difference independent of Y, it may or may not be that the preference differences between B and B' and between B' and B* are equal.

The last two independence conditions concern lotteries necessary to consider in developing utility functions. The utility independence notion is very similar to that of weak-difference independence. In Figure G-2, suppose that the consequence B is indifferent to the lottery yielding either A or C, each with a probability of .5. Then if X is utility independent of Y, the same preference relationship can be translated to all levels of Y. This means, for instance, that B' must be indifferent to a lottery yielding either A' or C', each with a probability of .5, and that B* must be indifferent to a lottery yielding either A* or C*, each with a probability of .5.

The utility independence concept is also not symmetrical: X can be utility independent of Y, and Y need not be utility independent of X. However, suppose that Y is utility independent of X in Figure G-2 and that A' is indifferent to a lottery yielding either A* with a probability of .6 or A with a probability of .4. Then B' must be indifferent to a lottery yielding B* with a probability of .6 or B with a probability of .4. The corresponding relationship holds for the C terms.

The additive independence condition is illustrated in Figure G-3. Consider the two lotteries L_1 and L_2 defined in the figure. Lottery L_1 yields equal .5 chances at the consequences (x°, y°) and (x', y'), and lottery L_2 yields .5 chances at each of (x°, y') and (x', y°). Note that both lotteries have an equal (namely, .5) chance at either x° or x', and both have an equal .5 chance at y° and y'. By definition, then, the marginal probability distributions on each of the attributes X and Y are the same in both lotteries. Thus, if X and Y are additive independent, one must be indifferent between lotteries L_1 and L_2. This same indifference condition must hold if either or both of x' and y' are changed in Figure G-3, because L_1 and L_2 would still have the same marginal probability distributions on the two attributes.

There is no meaning attached to the statement that X is additive independent of Y. Either X and Y are additive independent or they are not.

More-extensive discussions of all these independence conditions can be found in the technical literature. Some of the original sources are Debreu (1960), Luce and Tukey (1964), and Krantz (1964) for preferential independence; Krantz et al. (1971) and Dyer and Sarin (1979) for weak-difference independence; Keeney (1968), Raiffa (1969), and Meyer (1970) for utility independence; and Fishburn (1965, 1970) for additive independence. Keeney and Raiffa (1976) and von Winterfeldt and Edwards (1986) present detailed discussions of these conditions.

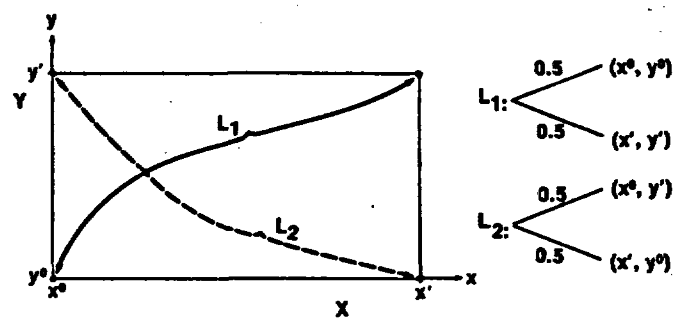

Figure G-3. Illustration of additive independence.

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G.1.3 FORMS OF THE MULTIATTRIBUTE UTILITY FUNCTION

The independence conditions appropriate for a given problem imply the functional form of the multiattribute utility function. For the repository siting problem, two results are worth mentioning.

Result 1. Given the attributes $X_1,\ldots,X_n$, $n \geq 2$, an additive utility function

$$u(x_1,\ldots,x_n) = \sum_{i=1}^{n} k_i u_i(x_i) \qquad \text{(G-2)}$$

exists if and only if the attributes are additive independent, where u_i is a utility function over X_i and the k_i are scaling constants.

Note that Equation G-2 is a special case of Equation G-1, and u can be assessed accordingly. The original proof of Equation G-2 is given by Fishburn (1965).

Result 2. Given attributes $X_1,\ldots,X_n$, $n \geq 3$, the utility function

$$u(x_1,\ldots,x_n) = \sum_{i=1}^{n} k_i u_i(x_i) + k \sum_{i=1}^{n} \sum_{j>i} k_i k_j u_i(x_i) u_j(x_j)$$
$$+ k^2 \sum_{i=1}^{n} \sum_{j>i} \sum_{h>j} k_i k_j k_h u_i(x_i) u_j(x_j) u_h(x_h)$$
$$+ \ldots + k^{n-1} k_1 \ldots k_n u_1(x_1) \ldots u_n(x_n) \qquad \text{(G-3)}$$

exists if and only if (X_1,X_i), $i = 2,\ldots,n$, is preferentially independent of the other attributes and if X_1 is utility independent of the other attributes.

With this utility function, one can assess the u_i on a scale of 0 to 1 and determine the scaling constants k_i to specify u. The additional constant k is calculated from the k_i, $i = 1,\ldots,n$.

If $\sum k_i = 1$, then $k = 0$, and if $\sum k_i \neq 1$, then $k \neq 0$. If $k = 0$, then clearly Equation G-3 reduces to the additive utility function

$$u(x_1,\ldots,x_n) = \sum_{i=1}^{n} k_i u_i(x_i). \qquad \text{(G-4)}$$

If $k \neq 0$, multiplying each side of Equation G-3 by k, adding 1, and factoring yields

$$ku(x_1,\ldots,x_n) + 1 = \prod_{i=1}^{n} [kk_i u_i(x_i) + 1], \qquad \text{(G-5)}$$

which is referred to as the multiplicative utility function. The proof of Result 2 is found in Keeney (1974). Both Pollak (1967) and Meyer (1970) used a more restrictive set of assumptions to derive Equation G-3.

If the condition that X_1 is weak-difference independent of the other attributes replaces the condition that X_1 is utility independent in Result 2, then the measurable-value function will necessarily be additive or multiplicative. That is, the u terms in Equations G-4 and G-5 can be replaced by w terms. This is proved by Dyer and Sarin (1979).

If a multiattribute utility function is either additive or multiplicative and if a measurable-value function is either multiplicative or additive, the multiattribute utility function and the measurable-value function will be identical if and only if the component utility function and the component measurable-value function for a single attribute are identical. From this condition and the conditions in Result 2, it follows that the respective component utility functions and the component measurable-value functions for each of the individual attributes must each be identical.

G.1.4 QUANTIFYING RISK ATTITUDES

The important concepts about risk attitudes are risk aversion, risk neutrality, and risk proneness. To discuss these concepts, we need to define a nondegenerate lottery, one where no single consequence has a probability equal to unity. There must be at least two consequences with finite probabilities. The following assumptions are mutually exclusive and collectively exhaustive when applied to any particular lottery:

- Risk aversion. One is risk averse if and only if the expected consequence of any nondegenerate lottery is preferred to that lottery. For example, consider a lottery yielding a cost of either 1 or 2 billion dollars, each with a chance of .5. The expected consequence of the lottery is clearly 1.5 billion dollars. If one is risk averse, then a consequence of 1.5 billion must be preferred to the lottery.

- Risk neutrality. One is risk neutral if and only if the expected consequence of any nondegenerate lottery is indifferent to that lottery.

- Risk proneness. One is risk prone if and only if the expected consequence of any nondegenerate lottery is less preferred than that lottery.

Given any single-attribute utility function, a measure developed by Pratt (1964) can be used to indicate its degree of risk aversion. The measure may be positive, zero, or negative, indicating risk aversion, risk neutrality, and risk proneness, respectively. Pratt also introduced more-sophisticated concepts of decreasing risk aversion, etc., which will not be discussed here. A summary of Pratt's original results, as well as several examples illustrating their use, is given by Keeney and Raiffa (1976).

The general shape of the utility function is completely determined by the attitude toward risk. This can all be stated in one concise result:

Result 3. Risk aversion (neutrality, proneness) implies that the utility function is concave (linear, convex).

These three cases are illustrated for both increasing and decreasing utility functions in Figure G-4, where it is assumed that the domain for attribute X ranges from a minimum x° to a maximum x^* and that u is scaled from 0 to 1.

In theory, by using the more sophisticated risk attitudes, such as decreasing risk aversion, one can specify not only the general shape of the utility function, but also an exact functional form. However, experience has shown that such fine tuning is rarely required for the single-attribute utility functions when they are part of a multiattribute formulation. It will almost always suffice to use a single-parameter utility function, where the single parameter quantifies the degree of risk aversion for the attribute in question. Specifically, the exponential and linear utility functions are collectively a fairly robust set of single-parameter forms for characterizing single-attribute utility functions.

Result 4. Classes of risk averse, risk neutral, and risk prone utility functions are

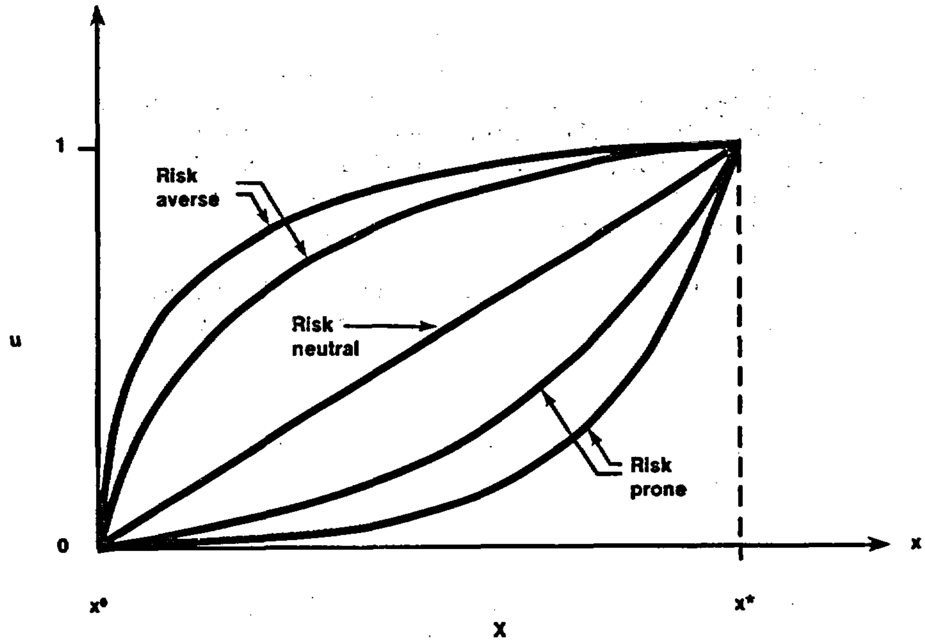
$$u(x) = a + b(-e^{-cx}), \qquad \text{(G-6a)}$$

$$u(x) = a + b(cx), \qquad \text{(G-6b)}$$

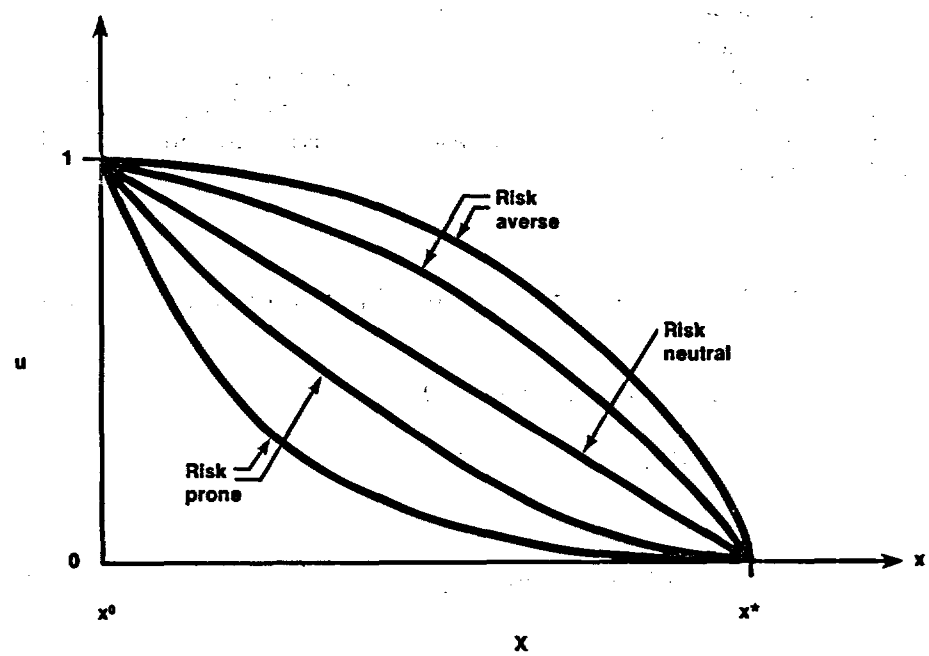
and

$$u(x) = a + b(e^{cx}), \qquad \text{(G-6c)}$$

respectively, where a and b > 0 are constants to ensure that u is scaled from 0 to 1 (or any scale desired) and c is positive for increasing utility functions and negative for decreasing ones.



(a) Increasing Utility Functions



(b) Decreasing Utility Functions

Figure G-4. Risk attitudes and utility functions.

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The parameter c in Equations G-6a and G-6c indicates the degree of risk aversion. For the linear case, Equation G-6b, parameter c can be set at +1 or -1 for the increasing and decreasing cases, respectively. More details about the exponential utility functions and discussions of other single-attribute utility functions are given by Pratt (1964) and Keeney and Raiffa (1976).

G.1.5 PROCEDURES FOR ASSESSING UTILITY FUNCTIONS

In the assessment of a multiattribute utility function, a decision analyst questions policymakers and decisionmakers about appropriate preferences for evaluating the alternatives. Using the results above, assessments are required to determine three types of information:

1. The appropriateness of the assumptions.
2. The individual functions u_i or w_i.
3. The scaling factors.

Obtaining this information is as much an art as it is a science. The approach for obtaining the necessary information is summarized in this section. A detailed explanation of how these assessments should be conducted is given by Keeney and Raiffa (1976) and Keeney (1980), who also illustrate them for many real cases.

G.1.5.1 Verifying independence conditions

All of the independence conditions are examined by looking for specific cases of preferences that contradict the assumption in question. If none are found, the assumption is assumed to be appropriate for the problem.

As an example, consider investigating whether (X_1,X_2) is preferentially independent of other attributes $X_3,\ldots,X_n$. First $X_3,\ldots,X_n$ are set at relatively undesirable levels (say, $x_3°,\ldots,x_n°$) and the preferences in the X_1, X_2 plane are examined. The decision analyst questions the policymakers to find pairs of consequences in this plane that are indifferent. Suppose $(x_1,x_2,x_3°,\ldots,x_n°)$ is indifferent to $(x_1',x_2',x_3°,\ldots,x_n°)$. Then $X_3,\ldots,X_n$ are changed to different levels (say $x_3^*,\ldots,x_n^*$) and the policymakers are asked whether $(x_1,x_2,x_3^*,\ldots,x_n^*)$ is indifferent to $(x_1',x_2',x_3^*,\ldots,x_n^*)$. A "yes" answer is consistent with preferential independence; a "no" answer is not. If such responses are consistent with preferential independence for several pairs of X_1 and X_2 and for several different levels of $X_3,\ldots,X_n$, then it is reasonable to assume that (X_1, X_2) is preferentially independent of $X_3,\ldots,X_n$.

Since the verification of weak-indifference independence or utility independence is identical in style, we shall discuss only the former here. Suppose we wish to ascertain whether X_1 is weak-difference independent of $X_2,\ldots,X_n$. Let us define the range of X_1 to go from $x_1°$ to x_1^*. We ask the policymaker for a level x_1' such that the preference difference from $x_1°$ to x_1' is equal to that from x_1' to x_1^*, given always that the other attributes are fixed at, say, $x_2°,\ldots,x_n°$. Then we can change the levels of $X_2,\ldots,X_n$ and repeat the process. If x_1' is still the level of X_1 such that the preference differences from x_1° and x_1' and from x_1' to x_1^* are equal, then it may be that X_1 is weak-difference independent of $X_2,\ldots,X_n$. If x_1' is not the level, then the condition cannot hold. If x_1' is found to be the level that splits the preference difference from x_1° to x_1^* for several levels of the other attributes, then it is reasonable to assume that X_1 is weak-difference independent of $X_2,\ldots,X_n$.

To examine the appropriateness of the additive independence condition, several pairs of lotteries with identical marginal probability distributions, such as those illustrated in Figure G-3, are presented to the policymakers. To make this simpler, all attributes but two can be fixed for all the consequences in both lotteries of a given pair. If the levels of the attributes that differ in consequences do cover the ranges of those attributes, and if each of the given pairs of lotteries is indifferent to the policymakers, then it is probably appropriate to assume that $X_1,\ldots,X_n$ are additive independent.

G.1.5.2 Assessing the individual functions

The individual functions that we want to assess are the single-attribute utility functions, denoted by u_i, which are also single-attribute measurable-value functions. In general, each of these is determined by assessing utilities for a few x_i levels and then fitting a curve. However, as indicated in the preceding discussion about risk aversion, the shape of the curve has a meaning in terms of the preferences.

Two types of value judgments are needed to determine the single-attribute utility functions. The first specifies the risk attitude and therefore determines the general shape of the utility function. The second identifies the specific utility function of that general shape.

Suppose we want $u(x)$ for attribute X for $x^\circ \leq x \leq x^*$. And since it is trivial to ascertain whether larger levels of X are preferred to smaller, let us assume larger levels are less preferred, as in the case with costs. To begin examining risk attitudes, we take a 50-50 lottery at the extremes of X and compare it with the expected consequence. That is, the policymakers are asked whether a 50-50 chance at each of x° and x^* is preferred to, indifferent to, or less preferred than the sure consequence $\bar{x} = (x^\circ + x^*)/2$. A preference for the sure consequence indicates that risk aversion may hold.

Next, the same line of questioning is repeated for the lower- and upper-half ranges of X. The lottery yielding equal chances at x° and $\bar{x}$ is compared with the expected consequence $(x^\circ + \bar{x})/2$. Preference for the sure consequence again indicates risk aversion. Similarly, a preference for the sure consequence $(\bar{x} + x^*)/2$ to a 50-50 lottery yielding either $\bar{x}$ or x^* also indicates risk aversion. If assessments for the entire range plus the upper and lower halves are consistent in terms of their risk implications, risk aversion is probably a very good assumption to make. If different implications are found and a reexamination indicates no errors in understanding, it is appropriate to divide the domain of X and search for sections exhibiting different risk attitudes. For instance, it may be that from x° to x' the policymakers are risk averse, but from x' to x^* risk neutrality is appropriate.

We have now determined that the risk attitude that implies one form of Equation G-6 is probably reasonable. If the form is G-6b, no additional assessments are necessary. The parameter c is set at +1 or −1, depending on whether the utility function is increasing or decreasing. Then the constants a and b are simply set to scale u from 0 to 1.

For the risk-averse and risk-prone cases, a little more effort is required. Suppose that the attribute is such that preferences increase for greater levels of the attribute and that the client is risk averse. Then from Result 4 it follows that a reasonable utility function is

$$u(x) = a + b(-e^{-cx}) \quad (b > 0,\ c > 0). \tag{G-7}$$

If u(x) is to be assessed for $x^\circ \leq x \leq x^*$, we might set

$$u(x^\circ) = 0 \quad \text{and} \quad u(x^*) = 1 \tag{G-8}$$

to scale u. Next, we shall need to assess the certainty equivalent for one lottery. In other words, we need to know a certainty equivalent $\hat{x}$ that is indifferent to the lottery yielding either x' or x'', each with an equal chance, where x' and x'' are arbitrarily chosen. Then the utility assigned to the certainty equivalent must equal the expected utility of the lottery, so

$$u(\hat{x}) = 0.5u(x') + 0.5u(x''). \tag{G-9}$$

Substituting Equation G-7 into Equations G-8 and G-9 gives us three equations with the three unknown constants a, b, and c. Solving for the constants results in the desired utility function.

Now let us return to the case of a constructed index with clearly defined level orders $x^\circ, x^1, \ldots, x^6, x^*$, where x° is least preferred and x^* is most preferred. Then we can again set a scale by Equation G-8 and assess $u(x^j)$, $j = 1, \ldots, 6$, accordingly. For each x^j, we want to find a probability p_j such that x^j for sure is indifferent to a lottery yielding either x^* with probability p_j or x° with probability $(1 - p_j)$. Then, equating utilities, we obtain

$$u(x^j) = p_j u(x^*) + (1 - p_j)u(x^\circ) = p_j \quad (j = 1, \ldots, 6). \tag{G-10}$$

For both the natural and the constructed scales, once a utility function is assessed, there are many possible consistency checks to verify the appropriateness of the utility function. One may compare two lotteries or a sure consequence and a lottery. The preferred situation should always correspond to the higher computed expected utility. If this is not the case, adjustments in the utility function are necessary. Such checking should continue until a consistent set of preferences is found.

Now suppose we wish to assess a measurable-value function w(x) for attribute X for $x^\circ \leq x \leq x^*$. Suppose that preferences increase in this range. Then we can scale w by

$$w(x^\circ) = 0, \quad w(x^*) = 1. \qquad \text{(G-11)}$$

To specify the shape of w, we investigate the qualitative character of the policymaker's preferences. For instance, we can take the point $x' = (x^\circ + x^*)/2$ halfway between x° and x^*, and ask for the midvalue point between x° and x'. Suppose it is one-third of the distance from x° to x'. Then we ask for the midvalue value point between x' and x^*. If it is also one-third of the distance from x' to x^*, a certain structure is implied since the ranges x° to x' and x' to x^* are the same. Suppose for any pair of points with this same range, the midvalue point is one-third of the distance from the less desired point to the more desired point. This would have very strong implications for the shape of w. In this case, it follows that

$$w(x) = d + b(-e^{cx}), \qquad \text{(G-12)}$$

where d and b are scaling constants to obtain consistency with Equation G-11 and the measurable value function has an exponential form with one parameter c.

The parameter c is determined from knowing the midvalue point for one pair of x levels. We could use the already determined point one-third of the distance from x° to x', for example. However, let us suppose we assess $\hat{x}$ to be the midvalue point for the range x° to x^*. Then, it follows from the definition of a measurable-value function that

$$w(x^*) - w(\hat{x}) = w(\hat{x}) - w(w^\circ). \qquad \text{(G-13)}$$

Combining this with Equation G-11 yields

$$w(\hat{x}) = 0.5, \qquad \text{(G-14)}$$

which can be substituted into Equation G-12 to determine the parameter c. The scaling parameters d and b can be determined from evaluating.

G.1.5.3 <u>Assessing the scaling constants</u>

The scaling constants, designated by the k's in Equations G-2 through G-5, indicate the value tradeoffs between the various pairs of attributes. Given attributes $X_1,\ldots,X_n$, there will be n scaling factors for the additive function and n + 1 for the multiplicative function. For now, let us designate the number of scaling constants by r. To determine these, we need to develop r independent equations with the r scaling constants as unknowns and then solve them.

To do this, we have, in general, a function u over $X_1,\ldots,X_n$ broken down into another function f with $u_1(x_1),\ldots,u_n(x_n)$ and $k_1,\ldots,k_r$ as arguments. Notationally,

$$u(x_1,\ldots,x_n) = f[u_1(x_1),\ldots,u_n(x_n),k_1,\ldots,k_r], \qquad \text{(G-15)}$$

where the form of f is determined from the independence conditions and the u_i are assessed as mentioned above. The easiest way to generate equations is to find two consequences x and y that are equally preferred by the policymakers. Then, clearly, u(x) = u(y), so

$$f[u_1(x_1),\ldots,u_n(x_n),k_1,\ldots,k_r] = f[u_1(y_1),\ldots,u_n(y_n),k_1,\ldots,k_r] \quad \text{(G-16)}$$

which is one equation with the unknowns $k_1,\ldots,k_r$.

In practice, it is usually best to fix n - 2 of the attributes and vary just two to obtain a pair of indifference consequences. If these two attributes are X_1 and X_2, then the question posed to the policymakers directly concerns the value tradeoffs between X_1 and X_2. The dialogue of an actual assessment concerning energy policy in Keeney (1980) illustrates the art involved in generating equations like Equation G-16 by using value tradeoffs. Operationally, if it turns out that some equations are redundant (i.e., not independent), additional equations can be generated as necessary.

G.1.6 CHECKING FOR CONSISTENCY

Once the information is obtained to specify a multiattribute utility function, it is important to consider this as a preliminary representation of the objective function. It provides a useful basis for any modification or improvement to better represent the value judgments appropriate for evaluating the alternatives. Indeed, in problems involving complex values, it is quite often the case that the initially expressed preferences are inconsistent to some degree. One of the major reasons for making the value judgments explicit is to identify inconsistencies, understand the basis for their existence, and then eliminate them to obtain a consistent representation of values. This does not mean, of course, that different individuals should have the same values.

The consistency checks can take several forms. There are a number of different sets of assumptions about independence conditions that can lead to the same multiattribute utility function or measurable-value function. More than one of the possibilities should be explored. Also, once the initial utility function is formulated, the implications of the utility function can be clearly displayed. These can then be appraised by a wide selection of interested individuals and by participants in the evaluation process.

G.2 ASSESSMENT OF THE MULTIATTRIBUTE UTILITY FUNCTION

This section presents the details of the assessment of the multiattribute utility function. Because the assessment of the preclosure utility function is more involved and because the assessment of the postclosure utility function is found in Chapter 3, this section focuses mainly on the former. However, assessments relevant to integrating the preclosure and postclosure utility functions are discussed.

The discussion begins with the perspective used in the assessment. The procedure used in the assessment is given next. Then the independence conditions that were verified and their implications for the form of the multiattribute utility functions are discussed. This is followed by assessments of the single-attribute utility functions and assessments of the value tradeoffs to specify the scaling factors. Finally, several consistency checks that were used are described.

G.2.1 PERSPECTIVE FOR THE ASSESSMENT

The utility function is necessary to quantitatively evaluate sites in terms of their impacts. As discussed in Chapter 2, the impacts of concern were categorized into implications for health and safety, environmental quality, socioeconomic conditions, and economic costs. The meanings of these four categories of preclosure impacts were further specified by the set of performance measures given in Table G-1. The performance measures for environmental and socioeconomic consequences required constructed scales that are defined in Tables G-2 through G-5, respectively. Table G-1 also contains a set of impact ranges for those performance measures. These ranges are meant to be broad enough to include all of the likely consequences that would occur if any of the five nominated sites were developed as a geologic repository.

The assessment of the utility function is done from a prescriptive viewpoint; that is, the value model developed is not supposed to describe or predict the behavior of government, but rather to help prescribe what actions should be taken by the government with respect to this problem to serve the interests of the citizens.

The value judgments expressed below were provided by managers in the Office of Civilian Radioactive Waste Management of the Department of Energy (DOE). It is this office that has the responsibility to advise the Secretary of Energy which three sites should be recommended for characterization. The Secretary of Energy must then recommend the three sites to the President.

G.2.2 PROCEDURE USED TO ASSESS THE UTILITY FUNCTION

The DOE managers who provided the value judgments necessary for the utility function were William J. Purcell, Associate Director for the Office of Geologic Repositories; Thomas H. Isaacs, Deputy Associate Director for the Office of Geologic Repositories; Ellison S. Burton, Director, Siting Division; and Ralph L. Stein, Director of the Engineering and Geotechnology Division. Others present during the assessments were Thomas P. Longo, a DOE staff person and the head of the methodology lead group (see Appendix A), and Ralph L. Keeney, a decision analyst from the University of Southern California who did the assessments.

The assessment process was conducted in three sessions that had distinct purposes. The first session was to establish an appropriate form for the utility function. The second session was to assess the value tradeoffs and single-attribute utility functions necessary to provide a specific utility function of that form. The third session was to reconfirm the key value judgments built into the utility function and to provide an opportunity for any changes. All three sessions were conducted with the managers before the

Table G-1. Objectives and performance measures

Objective	Performance measure	Impact Range Lowest Level	Impact Range Highest Level
	HEALTH-AND-SAFETY IMPACTS		
1. Minimize worker health effects from radiation exposure at the repository	X_1: repository-worker radiological fatalities	0	30
2. Minimize public health effects from radiation exposure at the repository	X_2: public radiological fatalities from repository	0	10
3. Minimize worker fatalities from nonradiological causes at the repository	X_3: repository-worker nonradiological fatalities	0	100
4. Minimize public fatalities from nonradiological causes at the repository	X_4: public nonradiological fatalities from repository	0	10
5. Minimize worker health effects from radiation exposure in waste transportation	X_5: transportation-worker radiological fatalities	0	10
6. Minimize public health effects from radiation exposure in waste transportation	X_6: public radiological fatalities from transportation	0	10
7. Minimize worker fatalities from nonradiological causes in waste transportation	X_7: transportation-worker nonradiological fatalities	0	10
8. Minimize public fatalities from nonradiological causes in waste transportation	X_8: public nonradiological fatalities from transportation	0	20
	ENVIRONMENTAL IMPACTS		
9. Minimize aesthetic degradation	X_9: constructed scale (see Table G-2)	0	6
10. Minimize the degradation of archaeological, historical, and cultural properties	X_{10}: constructed scale (see Table G-3)	0	5
11. Minimize biological degradation	X_{11}: constructed scale (see Table G-4)	0	5
	SOCIOECONOMIC IMPACTS		
12. Minimize adverse socioeconomic impacts	X_{12}: constructed scale (see Table G-5)	0	4
	ECONOMIC IMPACTS		
13. Minimize repository costs	X_{13}: millions of dollars	4000	19000
14. Minimize waste-transportation costs	X_{14}: millions of dollars	200	4200

Table G-2. Performance measure for aesthetic degradation attributable to the repository and the transportation network

Impact level	Aesthetic effects[a,b]
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] Major effects are defined as the following:

- The affected area contains components of the National Park system, National Wildlife Refuge system, National Wild and Scenic River system, National Wilderness Preservation system, National Forestlands, a comparably significant State resource area, or an aesthetic resource that is unique to the area. The locations of such components are such that--
  - Four or more key observation points or sensitive-receptor areas located in the resource area are on the line of sight or are within audible distance of the project and/or
  - Some key observation points or sensitive-receptor areas located on the line of sight or within audible distance of the project attract many visitors.
  - The locations of residences, population centers, major vistas, natural or cultural landmarks, public recreation areas, or public highways are such that these points are on the project's line of sight and are located in a visual setting that would significantly contrast with the project.
  - The locations of residences, population centers, major vistas, natural or cultural landmarks, public recreation areas, or public highways are such that the project would be audible and would exceed established notice criteria.

Table G-2. Performance measure for aesthetic degradation attributable to the facility and transportation network (continued)

[b] Minor effects are defined as the following:

- The affected area contains components of the National Park system, National Wildlife Refuge system, National Wild and Scenic River system, National Wilderness Preservation system, National Forestlands, a comparably significant State resource area, or an aesthetic resource that is unique to the area. The locations of such components are such that--

  - Three or fewer key observation points or sensitive-receptor areas located in the resource area are on the line of sight or are within audible distance of the project and/or

  - No key observation points or sensitive-receptor areas located on the line of sight or within audible distance of the project attract many visitors.

- The locations of residences, population centers, major vistas, national or cultural landmarks, public recreation areas, or public highways are such that these points are on the project's line of sight but are located in a visual setting that would not significantly contrast with the project.

- The locations of residences, population centers, major vistas, natural or cultural landmarks, public recreation areas, or public highways are such that the project would be audible but would not exceed established noise criteria.

Table G-3. Performance measure for the degradation of archaeological, historical, and cultural properties (historic properties)

Impact level	Impacts on historical properties[a]
0	There are no impacts on any significant historical properties
1	One historical property of major significance or five historical properties or minor significance are subjected to adverse impacts that are minimal or are amenable to mitigation
2	Two historical properties of major significance or ten historical properties of minor significance are subjected to adverse impacts that are minimal or are amenable to mitigation
3	Two historical properties of major significance or ten historical properties of minor significance are subjected to adverse impacts that are major and cannot be adequately mitigated
4	Three historical properties of major significance or 15 historical properties or minor significance are subjected to adverse impacts that are major and cannot be adequately mitigated
5	Four historical properties of major significance or 20 historical properties of minor significance are subjected to adverse impacts that are major and cannot be adequately mitigated

[a] The performance measure is defined by the following:

- Historical property of minor significance: A historical property that is of local or restricted significance, but does not meet the criteria of significance for the National Register of Historic Places (e.g., a homestead or miner's cabin that is of local importance but does not meet the criteria of the National Register; an archaeological site that is representative of a period of time of which there are many examples).

Table G-3. Performance measure for degradation of archaeological, historical, and cultural properties (historic properties) (continued)

- <u>Historical property of major significance</u>: A historical property that meets the criteria of significance 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) or a religious site highly valued by an Indian group (e.g., an Indian burial ground).

- <u>Minimal impacts</u>: Impacts that may alter the historical property, but will not change its integrity or its significance.

- <u>Major impacts</u>: Impacts that change the integrity or the significance of the historical property.

- <u>Amenable to mitigation</u>: The character of the historical property is such that it is possible to mitigate adverse impacts, reducing major impacts to minor or eliminating adverse impacts (e.g., impacts on an archaeological site that is significant because of the data it contains can be mitigated by excavating and analyzing those data; subsurface sites located within the controlled area may be protected under agreements made to guarantee that they will not be disturbed; a historical site can be adequately protected from vandals by erecting physical barriers).

- <u>Not amenable to mitigation</u>: The character of the historical property is such that impacts cannot be adequately mitigated because the value depends on the relationship of the historical property to its environment (e.g., a historical property of religious significance; a historical property that has value beyond the data contained; an archaeological site that is too complex for adequate excavation given current state-of-the-art techniques).

Table G-4. Performance measure for biological degradation

Impact level	Biological effects
0	No damage to species of plants or wildlife that are desirable, unique, biologically sensitive, or endangered or to any biological resource areas that provide habitats for such species.
1	Damage to, or destruction of, individuals of desirable species or portions of biological resource areas that provide habitats for the species, but such species or resource areas are nonunique, nonsensitive, nonendangered, and common throughout the region.
2	Biologically sensitive species or resource areas are within the affected area. The damage to, or destruction of, individuals of these sensitive species or portions of such resource areas does not threaten their regional abundance. Other affected biological resources are not unique in the region
3	Threatened and endangered (T&E) species and/or habitats for T&E species are within the affected area. The damage to, or destruction of, individuals of the T&E species or portions of the habitat does not threaten their regional abundance or Biologically sensitive species or resource areas are within the affected area. The damage to, or destruction of, individuals of these sensitive species or portions of such resource areas threatens their regional abundance Other affected biological resources are not unique in the region.
4	Threatened or endangered (T&E) species and/or habitats for T&E species are within the affected area. The damage to, or destruction of, individuals of the T&E species or portions of the habitats does not threaten their regional abundance and Biologically sensitive species or resource areas are within the affected area. The damage to, or destruction of, individuals of these sensitive species or portions of such resource areas threatens the regional abundance. Other affected biological resources are not unique in the region

Table G-4. Performance measure for biological degradation (continued)

Impact level	Biological effects
5	Threatened and endangered (T&E) species and/or habitats for T&E species are within the affected area. The damage to, or destruction of, individuals of the T&E species or portions of the habitats threatens their regional abundance and Biologically sensitive species or resource areas are within the affected area. The damage to, or destruction of, individuals of these sensitive species or portions of such resource areas threatens their regional abundance. Other affected biological resources are unique in the region.

Table G-5. Performance measure for socioeconomic impacts

Impact Level	Socioeconomic impacts equivalent to the following
0	Population growth of 2,000 persons is dispersed over a broad region with a population of 100,000. Public infrastructure--such as schools, protective services, fire services, water, sewer, and solid waste systems, and recreational facilities--are adequate to deal with repository-related growth. Transportation infrastructure and housing supply are also adequate. Because of the large population base, and diverse life-styles, values, and social structures, social disruptions are not expected. Direct and indirect employment of 1,500 during repository operation, in a region with total employment of 60,000, is not expected to lead to the area's economy becoming overly dependent on the repository. Repository activities are not incompatible with existing land uses such as agriculture, residential, or those related to tourism or local recreation, and no adverse impacts are expected to water resources. All land is state or federally-owned and no commercial, residential, or agricultural displacement is expected.
1	Population growth of 5,000 persons is dispersed over an area with a population of 50,000. Moderate upgrading of public infrastructure--such as schools, protective services, fire services, water, sewer, and solid waste systems, and recreation facilities--and of transportation infrastructure is required to accommodate repository-related growth in affected communities. Moderate (2 percent) increase in housing supply is required to accommodate growth. Despite the expected population growth, in-migrants have life-styles and values that are expected to match those of current residents; major social disruptions are not expected.

Table G-5. Performance measure for socioeconomic disruption impacts (Continued)

Impact Level	Socioeconomic impacts equivalent to the following
1 (continued)	Direct and indirect employment of 3,000 during repository operation in a region with total employment of 30,000 and a moderately diverse economy is not expected to lead to disruption of existing business patterns and economic dependency that cannot be avoided by applying standard economic planning measures. Repository activities are not incompatible with existing land uses such as agriculture, residential, or those related to tourism or local recreation; no adverse impacts are expected to water resources. One quarter of the land is privately owned and minimal commercial, residential, or agricultural displacement is expected.
2	Population growth of 5,000 persons is concentrated in a few communities in an area with a population of 50,000. Major upgrading of public infrastructure--such as schools, protective services, fire services, water, sewer, and solid waste systems, and recreation facilities--and of transportation infrastructure is required to accommodate repository-related growth in affected communities. A 10 percent increase in housing is also expected. More than a quarter of the residents have life-styles and values that are unlikely to match those of in-migrants. Direct and indirect employment of 3,000 during repository operation in a region with total employment of 30,000 and a moderately diverse economy is not expected to lead to disruption of existing business patterns and economic dependency that cannot be avoided by applying standard economic planning measures. Repository activities are somewhat incompatible with existing land uses such as agriculture, residential, or those related to tourism or local recreation and minor impacts are expected; minor diversion of water resources from other activities is also expected. Half of the land is privately owned and commercial, residential, or agricultural displacement is expected.

Table G-5. Performance measure for socioeconomic disruption impacts (Continued)

Impact Level	Socioeconomic impacts equivalent to the following
3	Population growth of 10,000 persons is concentrated in a few communities within an area with a population of 10,000. Major upgrading of public infrastructure--such as schools, protective services, fire services, water, sewer, and solid waste systems, and recreation facilities--and of transportation infrastructure is required to accommodate repository-related growth in affected communities. Considerable new housing (a 75 percent increase) is also expected.
	Affected communities have homogenenous life-styles, values, and social structure that do not match those of in-migrants; conflict between current and new residents is expected.
	Direct and indirect employment during repository operation of 5,000 in a region with 5,000 employees is expected to disrupt existing business patterns and to lead to substantial economic decline following the completion of repository operation.
	Negative impacts are expected to existing land uses such as agriculture, residential, or those related to tourism or local recreation; minor diversion of water resources from other activities is expected.
	All land is privately owned and commercial, residential, or agricultural displacement is expected.
4	Population growth of 10,000 persons is concentrated in a few communities within an area with a population of 10,000. Major upgrading of public infrastructure--such as schools, protective services, fire services, water, sewer, and solid waste systems, and recreation facilities--and of transportation infrastructure is required to accommodate repository-related growth in the affected communities. Considerable new housing (a 75 percent increase) is also expected.
	Affected communities have homogenenous life-styles, values, and social structure that do not match those of in-migrants; conflict between current and new residents is expected.

Table G-5. Performance measure for socioeconomic disruption impacts (Continued)

Impact Level	Socioeconomic impacts equivalent to the following
4 (continued)	Direct and indirect employment during repository operation of 5,000 in a region with 5,000 employees is expected to disrupt existing business patterns and to lead to substantial economic decline following the completion of repository operation. Repository activities are incompatible with existing land uses such as agriculture, residential, or those related to tourism or local recreation and negative impacts are expected; major diversion of area water sources is likely, resulting in impacts to development in the affected area. All land is privately owned and commercial, residential, or agricultural displacement is expected.

Table G-6. Parameters in the base-case multiattribute utility function and equivalent-consequence function

Performance measure	Impact range: Lowest level	Impact range: Highest level	Utility-function components: Value tradeoff Ki	Utility-function components: Component disutility functions Ci
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 non-radiological 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 non-radiological fatalities	0	10	1	x_7
X_8 = public nonradiological fatalities from transportation	0	20	4	x_8
X_9 = aesthetic impact (see Table 4-2)	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 impact (see Table 4-3)	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 impact (see Table 4-4)	0	5	0.3	$C_{11}(0)=0$, $C_{11}(1)=4$, $C_{11}(2)=10$, $C_{11}(3)=18$, $C_{11}(4)=40$, $C_{11}(5)=100$
X_{12} = socioeconomic impact (see Table 4-5)	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)	4000	19,000	1	x_{13}
X_{14} = transportation cost (millions of dollars)	200	4200	1	x_{14}

availability of information about the impacts describing the site performances in terms of the performance measures. The assessments reported below have not been changed since that time.

For the first session, to establish the form of the utility function, separate meetings were held with groups of two managers. Messrs. Burton and Stein participated in the first meeting, and Messrs. Purcell and Isaacs in the second. The reason for separate meetings was twofold. First, the managers were not familiar with the assessment procedure or the assesser (Keeney) and a smaller group provides a better opportunity for familiarization. Second, smaller groups reduce the likelihood that each individual does not fully participate in the assessment. Each of the meetings lasted from 3 to 4 hours. The implications were the same--namely, that the appropriate utility function was additive, as described in the next subsection.

The second session involved all four managers together. In examining the independence assumptions necessary to identify the appropriate form of the utility function, many value tradeoffs and single-attribute utility functions were necessarily specified in the first session. Thus, to some extent, the second session was a check on some implications of the first session.

In the second-session assessment of the value tradeoffs and single-attribute utility functions, each manager was asked to provide his own judgment first. An open discussion of the value judgments followed to resolve disagreements to the degree that this was appropriate (i.e., when the reasoning of one manager seemed appealing to another). There was no attempt to reach a consensus on the appropriate utility function for evaluating the nominated sites. Differences of opinion about this are certainly legitimate. The attempt was to reach agreement on a utility function thought to be reasonable for the base-case analysis. Any differences in values felt to be appropriate were to be included in the sensitivity analyses. The utility function presented in Section G.3 represents such a base-case utility function. The value judgments elicited in the second session, which lasted approximately 4 hours, are found later in this section. Both the first and the second sessions occurred in the same week.

The third session occurred 3 weeks after the first two. The base-case utility function had been specified from the value judgments in the interim and the substance in this appendix written to document it. The managers were asked to read this material before the session. In this session, there was a presentation of all the implications of the utility function. These included the independence assumptions, value tradeoffs, and single-attribute utility functions. The session lasted approximately 2 hours and included all the managers except Mr. Purcell, who was away on a business trip. He reviewed the implications from the written material. The managers concurred that the base-case utility function was a reasonable reflection of values for evaluating the nominated sites.

G.2.3 VERIFICATION OF INDEPENDENCE CONDITIONS

The procedures used to investigate each of the independence conditions discussed in Section G.1 are described below.

G.2.3.1 Preferential Independence

Each pair of performance measures in Table G-1 was found to be preferentially independent of all the other performance measures. Three examples are presented here.

Consider Figure G-5 which shows the consequence space for performance measures X_1 and X_5 representing respectively radiological fatalities (latent cancer) in workers at the geological repository and in transportation workers. The respective ranges go from 0 to 30 fatalities for repository workers and from 0 to 10 for transportation workers. The first question asked the DOE managers was whether consequence A or B in Figure G-5 was preferable, where consequence A represented 30 cancer fatalities in workers and none in transportation workers, and consequence B represented 10 fatalities in transportation workers and none in repository workers.

The respondents felt that consequence B was preferable. Next, consequence B was compared with consequence C, which represents five fatalities in repository workers and none in transportation workers. In this case, consequence C was preferred by the DOE managers. Next it was found that consequence D, representing 10 radiological fatalities in repository workers and none in transportation workers was indifferent to consequence B. The respondents were asked whether they had given any thought to the number of public fatalities that might be involved in making this value tradeoff between radiological fatalities in workers. The response was "no". This was an indication that the performance measures X_1 and X_5 were preferentially independent of the performance measures representing public fatalities. Similarly, the cost, environmental, and socioeconomic implications were found not to be of concern when making the value tradeoff between performance measures X_1 and X_5. Specifically, for instance, the questioning was repeated for explicit cases where the cost of repository was stated to be 8 billion and then 18 billion, and the same indifference indicates that the death of one repository worker from cancer is as undesirable as the death from cancer of a transportation worker. On being questioned, the DOE respondents agreed that this did represent the values they felt should be used to evaluate consequences in the problem. Indeed, further questioning indicated that the consequence of five cancer fatalities in transportation workers and five cancer fatalities in repository workers, indicated by E in Figure G-5, was indifferent to both consequences B and D. In general, the indifference curves over that consequence space were linear going through points involving an equal number of total fatalities to workers due to cancer.

In Figure G-6, the pair of performance measures X_7 and X_8 were the examined for preferential independence. Specifically, X_7 represents nonradiological fatalities in transportation workers and X_8 the nonradiological fatalities in the public that are due to waste transportation. The numbers of fatalities range from 0 to 10 for workers and from 0 to 20 for the public, and are essentially all attributable to possible traffic accidents or accidents between trains carrying the waste and automobiles. In Figure G-6 consequence A with 10 worker fatalities and no public fatalities was much preferred to consequence B with 20 public fatalities and no worker fatalities. Consequence A was also preferred to consequence C, which entails 10 public fatalities and no worker fatalities. It was found that consequence A was indifferent to consequence D, which is 2.5

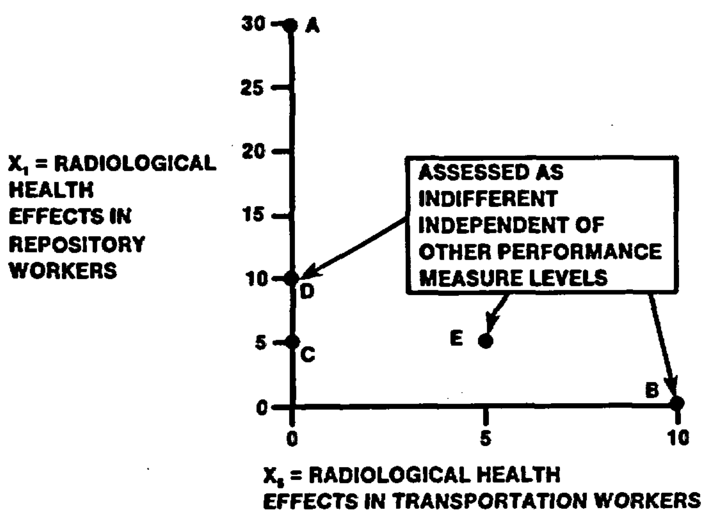

Figure G-5. Verification that $\{X_1, X_5\}$ are preferentially independent of other performance measures.

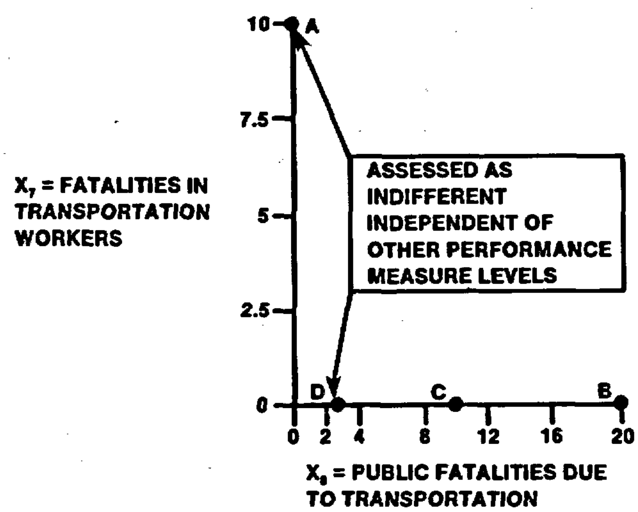

Figure G-6. Verification that $\{X_7, X_8\}$ are preferentially independent of other performance measures.

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public fatalities. It was clearly stated that this indifference did not depend on the other numbers of public or worker fatalities due to radiation or due to accidents at the facility. This value tradeoff also did not depend on environmental, socioeconomic, or economic consequences. Hence, performance measures X_7 and X_8 were preferentially independent of the other performance measures. In this context, it was also verified that the indifference curves over worker and public fatalities due to transportation accidents were linear and evaluated a public fatality as four times more significant than a worker fatality. The reasons for such an evaluation are discussed in Section G.4.

Figure G-7 shows the indifference that was found between the socioeconomic performance measure X_{12} and the repository-cost performance measure X_{13}. Specifically, no socioeconomic impact (level 0) and a cost of 5,500 million dollars was indifferent to the worst level of socioeconomic impact (level 4) and a repository cost of 5,000 million dollars. This value tradeoff was independent of the levels of the other performance measures. Furthermore, the DOE managers were always indifferent to accepting an additional cost of 500 million dollars to alleviate entirely the socioeconomic implications of a level 4 impact.

G.2.3.2 Utility independence

Utility independence was specifically verified for two performance measures, public fatalities due to transportation accidents, X_8, and repository costs, X_{13}. For X_8, the DOE managers were presented a lottery, shown in Figure G-8, with a 50-50 chance of either 20 public fatalities or otherwise no public fatalities and asked to compare it with a sure loss of five members of the public in transportation accidents. Although clearly undesirable, the certain consequence of 5 fatalities was better than the lottery involving the 50-50 chance of 20 fatalities. When the certain consequence was changed to 15 fatalities, it was deemed less preferable than the lottery. Finally, 10 was selected as the number of fatalities indifferent to the lottery. That response was independent of the levels of other attributes in the problem. Specifically, the same questions were repeated, and the same responses elicited, when it was explicitly stated that the cost of the repository was 6 billion and then 18 billion. Similar questions were repeated with different fixed levels of socioeconomic and environmental implications, and the same response of 10 public fatalities being indifferent to the lottery was obtained. Hence, performance measure X_8 was utility independent of the other attributes.

Figure G-9 shows a lottery for the costs of the repository. It involves a 50-50 chance of either 20 billion dollars or 5 billion dollars in cost. This lottery was preferred to a certain cost of 16 billion dollars and less preferred than a repository cost of 10 billion dollars. It was indifferent to a certain cost of 12.5 billion dollars, which is the average of the lottery. This indifference did not depend on the level of the other performance measures, indicating that X_{13} was utility independent of the other performance measures.

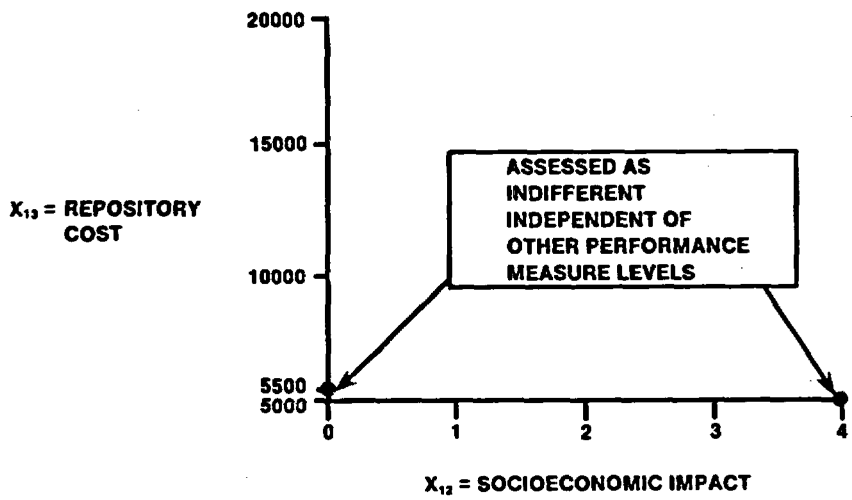

Figure G-7. Verification that $\{X_{12}, X_{13}\}$ are preferentially independent of other performance measures.

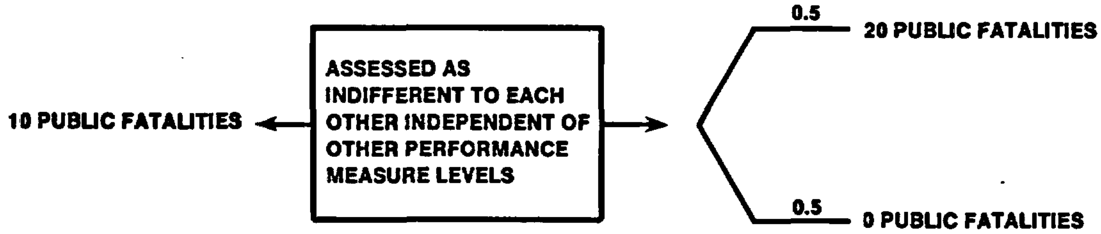

Figure G-8. Verification that X_8, noncancer public fatalities due to transportation, is utility independent of the other performance measures.

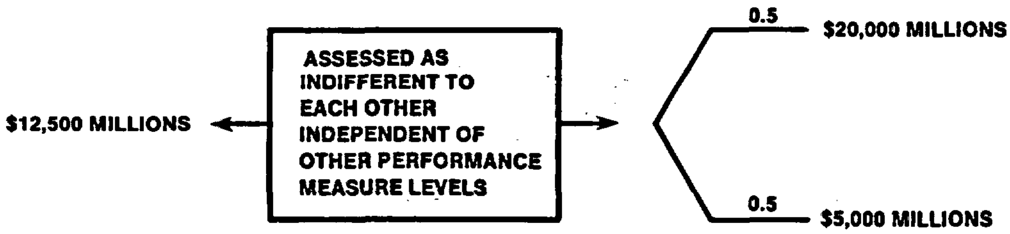

Figure G-9. Verification that X_{13}, repository costs, is utility independent of the other performance measures.

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G.2.3.3 Weak-difference independence

Exactly like the utility-independence assumptions, weak-difference independence was examined for performance measures X_8 and X_{13}. For instance, with regard to public fatalities, the DOE managers were asked what number of fatalities X_8 was such that the difference between 0 and x_8 fatalities was as significant as the difference between x_8 and 20 public fatalities. The level of x_8 was varied until the two ranges were equally significant. This occurred when x_8 was 10, and the response was independent of the levels of the other performance measures, indicating that X_8 was weak-difference independent of the other performance measures. Because the midvalue point of 10 fatalities was identical with the certainty equivalent of 10 fatalities obtained in assessing utility independence for X_8 in Figure G-8, it indicated that the utility function and the measurable-value function for X_8 were one and the same.

Regarding repository costs, it was determined that the change in costs from 5 billion to 12.5 billion dollars was as significant as the increase in cost from 12.5 billion to 20 billion dollars. This also did not depend on the level of the other performance measures. Hence, it seemed appropriate to assume that X_{13} was weak-difference independent of the other performance measures.

G.2.3.4 Additive independence

Three pairs of performance measures were explicitly examined for additive independence. The first involved performance measures X_7 and X_8. The DOE managers were shown the two lotteries in Figure G-10 and asked whether they were indifferent between these lotteries or had a preference for one over the other. It was pointed out that in each case there was an equal chance that the number of worker fatalities due to transportation accidents would be either 0 or 10 and that the number of public fatalities due to transportation accidents would have an equal chance of being either 0 or 20. The only difference between the two lotteries is the manner in which the combinations of the fatalities would occur. Specifically, with the first lottery, one would have either 20 public and 10 worker fatalities or no public and worker fatalities. With the second lottery, one would have either the higher number of worker fatalities and no public fatalities or the higher number of public fatalities and no worker fatalities. The DOE respondents were indifferent between these two lotteries, indicating that performance measures X_7 and X_8 were additive independent of the other performance measures.

Figure G-11 indicates the examination of performance measures X_8 and X_{13} for additive independence. With both lotteries, there is is an equal chance that the number of public fatalities from transportation accidents will be either 0 or 20. Also, with each lottery there is an equal chance that the repository cost will be either 5,000 or 15,000 million dollars. The only difference in the two lotteries is how the consequences are paired together. The DOE respondents were also indifferent between these two lotteries. Hence, X_8 and X_{13} were additive independent.

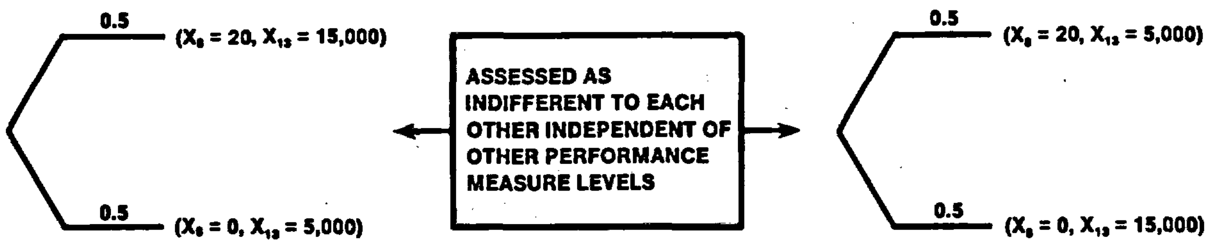

Figure G-10. Verification that X_7, noncancer worker fatalities due to transportation, and X_8, noncancer public fatalities due to transportation, are additive independent.

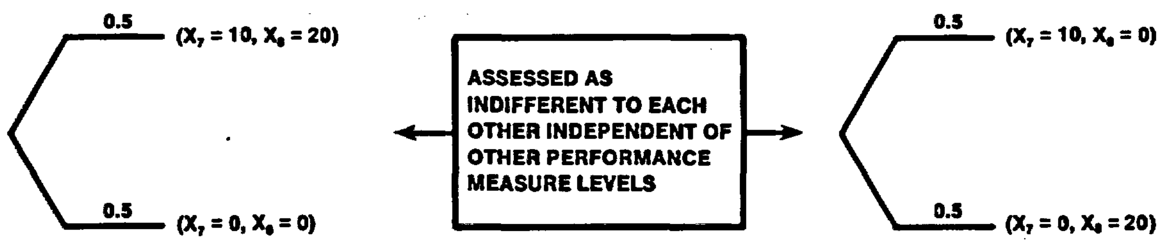

Figure G-11. Verification that X_8, noncancer public fatalities due to transportation, and X_{13}, repository costs, are additive independent.

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Finally, Figure G-12 was used to examine whether a preclosure measure of fatalities and a postclosure measure of radiation releases were additive independent. Specifically, performance measures X_2 and X_{15}', the number of postclosure cancer fatalities induced in the public by radiation, were utilized. Both lotteries in Figure G-12 have equal chances of either 0 or 10 preclosure public cancer fatalities due to the repository, and an equal chance at either 0 or 200 postclosure cancer fatalities due to the repository. The DOE respondents were indifferent between these two lotteries, indicating that the pair of performance measures X_2 and X_{15}' were additive independent of the other performance measures. This suggests that preclosure fatalities X_2 and postclosure radiation releases X_{15} should be additive independent.

G.2.3.5 Form of the multiattribute utility function

The independence assumptions verified in this problem are sufficient to imply that the preclosure multiattribute utility function must be of the additive form given by Equation G-4. Furthermore, because the component utility functions for public transportation fatalities and for repository costs were identical with the measurable-value functions for those performance measures, the multiattribute utility function must also be a measurable-value function.

G.2.4 COMPONENT UTILITY FUNCTIONS

As a result of the assessments involving the independence assumptions, a good deal of information was already available on the component utility functions. For instance, from Figures G-8 and G-9 it was clear that the component utility functions for public transportation fatalities and repository costs had to be linear, which was consistent with a risk-neutral attitude. Then, because of the linear indifference curves between the performance measures X_8 and X_{13} and the other health-and-safety and cost performance measures, it followed that all of the component utility functions for the health-and-safety and cost performance measures had to be linear. However, many direct assessments were made to verify that this was indeed the case.

As an example, consider preclosure nonradiological fatalities in repository workers, represented by performance measure X_3. The range on this goes from 0 to 100 fatalities. The DOE respondents felt that a lottery with an equal chance at either 0 or 100 such fatalities was indifferent to a situation with a certain consequence of 50 fatalities. This indicated that the component utility function was linear.

The utility functions for the performance measures involving constructed scales--namely, those concerning environmental and socioeconomic consequences--were assessed differently. The assessments were done by specialists involved in constructing the respective performance measures (see Appendix A), and measurable-value functions were assessed. Let us indicate the assessments for the four performance measures in question. For performance measure X_9, which is concerned with aesthetic impacts, the scale

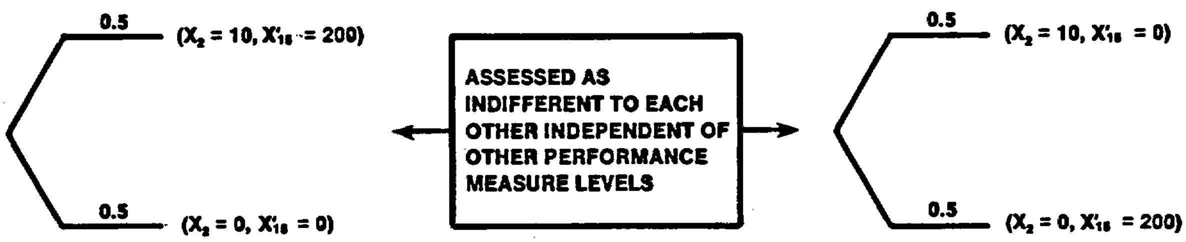

Figure G-12. Verification that X_2, preclosure public health effects due to repository radionuclide releases, and X'_{15}, a measure of postclosure health effects due to reposiotry radionuclide releases in the first 10,000 years, are additive independent.

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had seven levels, as shown in Table G-2. Level 0 corresponded to no impact, and level 6 to the greatest impact. We wished to scale the measurable-value function from 0 to 1, so a value of 1 was assigned to 0 impact, and a value of 0 to a level 6 impact. The aesthetic scale involved major effects and minor effects. The respondent was asked whether a major effect was two times as significant as a minor effect, or less than twice as significant or more than twice as significant. The response was that it was more than twice as significant. Next, we asked whether a major effect was five times as significant as a minor effect, or less or more. Again, the response was "more". It was determined that a major effect was 10 times as significant as a minor effect. Furthermore, the respondents felt that two major effects were twice as significant as one major effect and that two minor effects were twice as significant as one minor effect. Thus, the measurable-value function, and the component utility function, since they must be the same, is given by

$$u_9(0) = 1, \quad u_9(1) = 0.97, \quad u_9(2) = 0.94, \quad u_9(3) = 0.91,$$

$$u_9(4) = 0.67, \quad u_9(5) = 0.33, \quad u_9(6) = 0.$$

The performance measure for archaeological impact, X_{10}, is shown in Table G-3. It has six levels, ranging from 0 for no impact to 5 for the maximum impact. As seen by the construction of the scale itself, the respondent felt that one historical property of major significance was equivalent to five historic properties of minor significance. It was determined that a major adverse impact on two historical properties was twice as significant as a major adverse impact on one historical property and that the same relationship was true for minor adverse impacts. It was also determined that a minor impact was approximately one-fourth as significant as a major impact on a historical property. Collectively, these responses allowed the construction of the following measurable-value function, which is also a component utility function, for archaeological impacts:

$$u_{10}(0) = 1, \quad u_{10}(1) = 0.88, \quad u_{10}(2) = 0.77, \quad u_{10}(3) = 0.44,$$

$$u_{10}(4) = 0.22, \quad u_{10}(5) = 0.$$

The scale for biological impacts goes from no impact, indicated by level 0, to the impact indicated by level 5 in Table G-4. A measurable value of 1 was assigned to the level 0, and a value of 0 was assigned to the level 5. It was first determined that the significance of a change from level 5 to level 4 was 1.5 times as significant as the change from level 4 to the no-impact level 0. This indicated that the measurable value of level 4 had to be 0.6. Going from level 4 to level 3 eliminated slightly more than half the negative biological impacts associated with level 4, so that change in value had to be slightly greater than the significance of the change from level 3 to level 0. Thus the measurable value of level 3 was set at 0.82. The respondent felt that a change from level 3 to level 2 was more valuable than a change from level 2 to level 1 and that a change from level 2 to level 1 was more valuable than a change from level 1 to level 0. Consistent with this is the following measurable value function and utility function:

$$u_{11}(0) = 1, \quad u_{11}(1) = 0.96, \quad u_{11}(2) = 0.9, \quad u_{11}(3) = 0.82,$$

$$u_{11}(4) = 0.6, \quad u_{11}(5) = 0.$$

With regard to the socioeconomics performance measure X_{12} defined in Table G-5, the no-impact level 0 was assigned a measurable value of 1, and the impact level 4 was assigned a value of 0. The significance of the change in impact from level 4 to level 3 was deemed equal to the significance of a change from level 3 to level 2. Each of these changes was felt to be twice as significant as a change from level 2 to level 0. Also, the importance of a change from level 2 to level 1 was 1.5 times as important as a change from level 1 to level 0. As a result, the measurable-value function, and the component utility function, is

$$u_{12}(0) = 1, \quad u_{12}(1) = 0.92, \quad u_{12}(2)=0.8, \quad u_{12}(3) = 0.4, \quad u_{12}(4) = 0.$$

G.2.5 VALUE TRADEOFFS

As was the case with the component utility functions, a good deal of information about the value tradeoffs was available directly from the independence assessments. All the value tradeoffs, which were made by the DOE managers, are presented here. The reasons for, and the appropriateness of, the value judgments are discussed in Section G.4. A sensitivity analysis also investigated the implications of these value judgments for the evaluation of the nominated sites.

From Figure G-5 and the related discussion, it was clear that the DOE managers felt that a cancer fatality in a repository worker should be considered equivalent to a cancer fatality in a worker involved in transporting the radioactive waste. The same logic was used regarding the pairs of performance measures X_2 and X_6, X_3 and X_7, and X_4 and X_8. Basically, these value tradeoffs indicated that radiological fatalities in the public were equivalent whether they resulted from transportation or from the repository, that nonradiological fatalities in workers were equivalent whether they resulted from working at the repository facility or in transportation, and that nonradiological fatalities in the public were equivalent whether they resulted from the repository or transportation.

An important value tradeoff involves the death of an individual member of the public from radiological or nonradiological causes. It was decided that the appropriate evaluation scheme would equate these. In addition, the DOE managers felt that it was appropriate to equate radiological and nonradiological fatalities in workers.

The value tradeoff between public fatalities and worker fatalities is shown in Figure G-6. Specifically, it was felt that a public fatality should be considered four times as important as a worker fatality.

The value tradeoff between repository cost and transportation cost was easy: the DOE managers felt that a dollar of cost in one was equivalent to a dollar of cost in the other. The value tradeoffs between costs and the other performance measures were, however, more difficult.

The value tradeoff between preclosure public fatalities and costs was felt to be 4 million dollars for each statistical fatality; that is, up to 4 million dollars should be spent to prevent one statistical fatality from either radiation exposure or accidents, such as traffic accidents, involving the public. Because such a value tradeoff is clearly sensitive and crucial to any evaluation, the reasonableness of this is discussed in detail in Section G.4 and the sensitivity analysis varied this value tradeoff over a wide range.

The value tradeoffs for the environmental and socioeconomic performance measures were assessed by asking for the maximum increase in repository costs that would be justified for reducing a particular impact from the maximum level to the zero level. To alleviate the aesthetic effects associated with a level 6 impact, the DOE respondents felt that an additional cost of 100 million dollars would be justifiable. This means, for instance, that a repository with no aesthetic impact that cost 100 million dollars more than a repository that had a level 6 aesthetic impact would be equally desirable.

To preclude the archaeological impacts associated with level 5 on performance measure X_{10}, the DOE respondents were willing to spend up to 20 million dollars. To preclude the biological impacts associated with level 5 on performance measure X_{11}, they were willing to spend an additional 30 million dollars. With regard to the socioeconomic performance measure X_{12}, the respondents were willing to spend up to 500 million dollars to preclude the impacts associated with level 4 (i.e., to reduce the impacts to level 0).

A value tradeoff is necessary to provide some guidance for an appropriate manner to combine preclosure and postclosure utility functions. This was addressed in the composite analysis by conducting a sensitivity analysis for the entire range of possible value tradeoffs. Since the implications of the analysis were similar over essentially this whole range, little effort was focused on obtaining an appropriate judgment for this potentially controversial value tradeoff.

G.2.6 CONSISTENCY CHECKS

Many consistency checks were made in the course of these assessments. The independence checks were redundant in many situations. For instance, if the pair of performance measures X_1 and X_2 is preferentially independent of the others and if the pair X_2 and X_3 is preferentially independent of the others, then it follows that the pair X_1 and X_3 must also be preferentially independent of the others. However, in several situations, the latter was explicitly checked.

As discussed with regard to the utility independence and weak-difference independence assumptions, the situations were checked for two attributes--public fatalities due to transportation, X_8, and facility cost X_{13}. Only one would be sufficient to use Result 2 and to show that the multiattribute utility function and measurable-value function must be one and the same, given the preferential independence assumptions.

Similarly, it was necessary to verify for additive independence only one of the situations represented in Figures G-10 through G-12; the others should have been additive independent in order to be consistent. Independent verification showed that this was indeed the case.

With regard to the linearity of the component utility functions, this was consistent with the linear indifference curves between pairs of performance measures once it is verified that one of the component utility functions is linear. It also happens that linear utility functions and linear indifference curves imply that the multiattribute utility function is additive, which provides an additional check on the overall structure of the utility function. As a check of the value tradeoffs, implications of pairs of value tradeoffs on overlapping performance measures were redundantly assessed. For instance, 4 million dollars was assessed as indifferent to one statistical public fatality and one public fatality was assessed as indifferent to four worker fatalities. This implies that one worker fatality must be indifferent to 1 million dollars, which was also the assessed value tradeoff. After the assessment, all the DOE managers reviewed the implications of the utility function discussed in Section G.3 and the appropriateness of this assessment in Section G.4.

G.3 THE MULTIATTRIBUTE UTILITY FUNCTION

This section presents the utility function implied by, and consistent with, the assessments in Section G.2. The resulting multiattribute utility function will be called the "base-case utility function." First the preclosure utility function is presented. Then the aggregate preclosure and postclosure utility function is given. Next the implications of the utility functions are listed, and finally variations that are useful to examine in sensitivity analyses are considered.

G.3.1 THE BASE-CASE PRECLOSURE UTILITY FUNCTION

Because of the preferential independence conditions and the utility independence conditions verified in the assessment process, Result 2 of Section G.1 implied that the multiattribute utility function must be either additive or multiplicative. The verification of the additive independence assumption as part of the assessments implied that the specific case must be the additive utility function

$$u(x_1, \ldots, x_{14}) = \sum_{i=1}^{14} k_i u_i(x_i), \qquad \text{(G-17)}$$

where u is the multiattribute utility function scaled from 0 to 1; the $u_i (i = 1,\ldots,14)$ are the component utility functions scaled from 0 for the worst level to 1 for the best level; and the scaling factors represented by the $k_i (i = 1,\ldots,14)$ are each between 0 and 1 and sum to 1.

The component utility functions specify the relative desirability of the different levels of each single performance measure over the ranges indicated in Table G-1. Figure G-13 illustrates the component utility functions. Thus, for instance, with regard to the component utility function u_1, the best level of zero fatalities and the worst level of 30 fatalities are respectively assigned utilities of 1 and 0, meaning $u_1(0) = 1$ and $u_1(30) = 0$. Furthermore, it can be calculated from u_1 that $u_1(15) = 0.5$. Since u_1

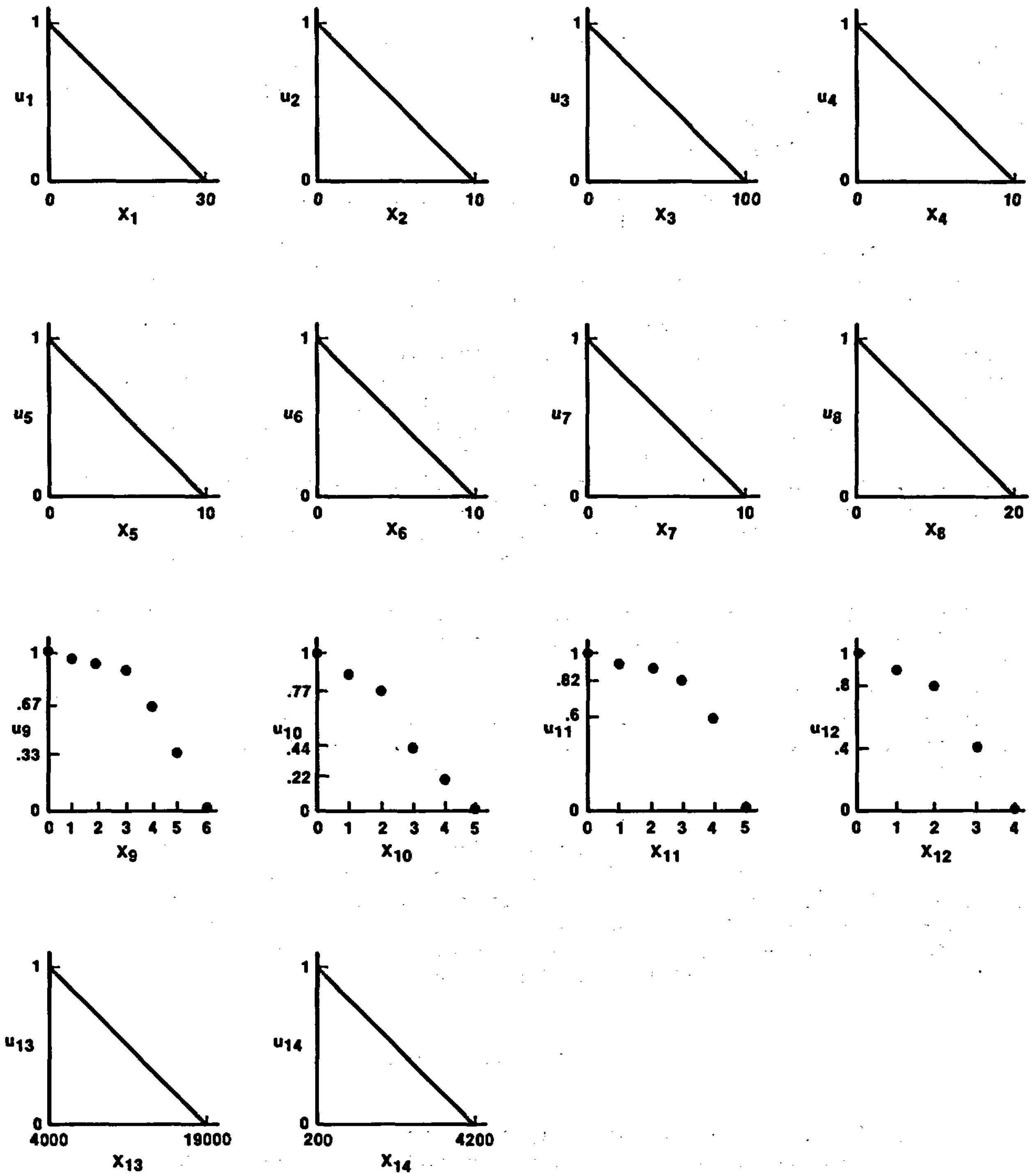

Figure G-13. The assessed component utility functions.

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is assessed to compare lotteries, a lottery that yields a 0.5 chance of 30 fatalities and a 0.5 chance of zero fatalities has an expected utility of 0.5. Thus, this should be indifferent to 15 certain fatalities, which has the same utility. This indifference must hold to be consistent with the assessments that the preferences were linear.

The misinterpretation of the scaling factors, the k_i's, is a common mistake in appraising multiattribute utility studies. Specifically, the scaling factors <u>do not</u> indicate the relative importance of the different performance measures. In fact, there is no clear meaning to the statement that one performance measure (or the objective associated with it) is more important that another. In order to make the meaning of "more important" unambiguous, it is necessary to attach a range to each performance measure. Thus, for instance, it would be correct to say that if the scaling factor associated with performance measure X_3, nonradiological fatalities in repository workers, was greater than the scaling factor associated with performance measure X_4, nonradiological public fatalities due to the repository, then the relative importance of going from the worst level of nonradiological worker fatalities to the best level is more important than going from the worst level of nonradiological public fatalities to the best level. However, this may occur because there is a range of 100 worker fatalities vs. 10 public fatalities. It may <u>not</u> be the case that an individual worker fatality is evaluated as more important than an individual public fatality in this context. Indeed, just the opposite may be true. To illustrate this important point, the assessments in Section G.2 indicated that a nonradiological public fatality is considered four times more important than a nonradiological worker fatality. Yet, because the range for repository worker fatalities is 10 times as great as the range of nonradiological public fatalities, the scaling factor k_3 would be 2.5 times the scaling factor k_4 (calculated as 1/4 times 10).

For this problem, the assessed value judgments are such that the additive utility function can be written in a form much easier to interpret than Equation G-17. Because the preferences over each performance measure decrease with increasing impact levels and because the component utility functions are linear for each of the performance measures with natural scales, the multiattribute additive utility function can be written as

$$u(x_1,\ldots,x_{14}) = 121 - 1/200\ [\sum_{i=1}^{14} K_i C_i(x_i)], \qquad \text{(G-18)}$$

where the $C_i(i = 1,\ldots,14)$ are directly interpretable as units of impact for the performance measures with natural scales and percentages of the range of impacts for performance measures with the constructed scales and the $K_i(i = 1,\ldots,14)$ represent the value tradeoffs.

The interpretation of the K_i scaling factors is easy. For instance, the scaling factor $K_1 = 1$ is one, meaning that an additional cost of 1 million dollars was assessed as equivalent to a statistical worker fatality induced by radiation exposure at the repository. The scaling factor $K_2 = 4$, meaning that the relative value of one additional cancer induced in the public by radioactive emissions from the repository is equivalent to 4 million dollars. For the socioeconomics performance measure, the assessed value tradeoff was that it is worth 500 million dollars to reduce the socioeconomic impacts associated with the worst level (i.e., level 4) of that performance measure to level 0, which represents no adverse socioeconomic impacts. Hence, $K_{12} = 5$, since it is worth 5 million dollars to reduce socioeconomic impacts by 1 percent of the range of impacts. The performance measures for both of the cost attributes are identically 1, implying that a million dollars is worth a million dollars. The specific values that were assessed for C_i and K_i are given in Table G-6.

Since preferences decrease with increasing impact levels, the minus sign is needed in front of the 1/200 term in Equation G-18 and the C_i can be considered as component disutility functions. The factors 121 and -1/200 in Equation G-18 are necessary to scale the utility from 0 to 100, where 100 is chosen to represent a particularly desirable set of impacts for all performance measures and 0 represents a particularly undesirable set of impacts for all performance measures. For this purpose, the ranges of the performance measures listed in Table G-1 (repeated in Table G-6) were chosen to be broad enough to include all possible impacts for the sites being evaluated. The utilities of 0 and 100 are assigned to sets of impacts represented respectively by the worst levels and the best levels in Table G-6. Because the utility function is additive and because the component utility function for repository cost is linear, it is particularly easy to interpret units, referred to as utiles, of the multiattribute utility function (Equation G-18) in terms of equivalent costs. Specifically, one utile is equivalent in value to 200 million dollars.

A final comment about the multiattribute utility function is in order. Because of the weak-difference independence verified in the assessments discussed in Section G.2 and because the component measurable value function for costs was the same as the component utility function for costs, the multiattibute utility function represented in Equation G-18 is also a measurable-value function. This means that the difference in the utility of two consequences can be used as a measure of the relative importance of the difference between those two consequences. Hence, differences in utilities can be used to rank the relative importance between consequence pairs.

G.3.2 PRECLOSURE AND POSTCLOSURE UTILITY FUNCTIONS

To evaluate the overall implications of various nominated sites, it is necessary to combine the preclosure and postclosure multiattribute utility functions. This results in the overall site utility $u_s(S_j)$ for site S_j calculated from

$$u_s(S_j) = k_{Pre}u_{pre}(x_1,\ldots,x_{14}) + k_{Post}u_{Post}(x_{15},x_{16}) \qquad \text{(G-19)}$$

where u_{pre} is u given in Equation G-18, u_{post} is given in Chapter 3, and $k_{Pre} + k_{Post} = 1$. The k_{pre} and k_{post} are assessed by using value tradeoffs between preclosure and postclosure impacts. Their interpretation relates to the relative importance of the collective ranges of the preclosure performance measures and the postclosure performance measures, respectively.

G.3.3 IMPLICATIONS OF THE MULTIATTRIBUTE UTILITY FUNCTION

There are numerous implications of the utility functions that were not directly verified in the assessment. This is the case even though there were redundant verifications to check the consistency of the assessed multiattribute utility function.

Some of the major implications of the base-case utility function are readily evident from Figure G-13. Specifically, it is clear that the component utility functions for all of the performance measures involving a natural scale (i.e., the health-and-safety, and cost performance measures) are linear.

The implications of the utility function with respect to independence conditions are not directly observable from the utility function without some prior knowledge of multiattribute utility theory. Specifically, the following implications hold:

- Each pair of performance measures is preferentially independent of the set of remaining performance measures.
- Each individual performance measure is utility independent of the set of remaining performance measures.
- Each individual performance measure is weak-difference independent of the set of remaining performance measures.
- Each pair of performance measures is additive independent of each other when the levels of the remaining set of performance measures are fixed.

G.3.4 VARIATIONS OF THE MULTIATTRIBUTE UTILITY FUNCTION USEFUL FOR SENSITIVITY ANALYSIS

The conduct of the analysis is important. In this analysis, the value judgments are introduced sequentially, beginning with those that might be considered less controversial. For example, the judgment that a dollar of repository cost is as significant as a dollar of transportation cost is likely to be less controversial than value tradeoffs between costs and environmental impacts. After introducing the less controversial value tradeoffs into the analysis, the alternatives are carefully examined to see what implications can be drawn. Implications from this stage of the analysis may have broad acceptance from individuals representing a wide variety of viewpoints about appropriate value judgments for the problem. Even a partial ranking of the nominated sites may be of substantial help. Then more controversial value judgments can be introduced and the nominated sites further examined. The intention is to gain as many insights from the analysis as possible while making the weakest, and therefore the most widely acceptable, value judgments and assumptions. With this analysis, the implications for the ranking of the nominated sites is rather strong based on the analysis prior to the introduction of what should be the most difficult and controversial value tradeoffs.

A crucial element of the multiattribute utility analysis is the sensitivity analyses that are conducted. The intent is to vary over reasonable ranges any of the possible inputs that could substantially affect the relative desirability, and hence the ranking, of the nominated sites. These sensitivity analyses are intended to indicate which judgments or data are crucial to the conclusions drawn from the analysis. They also suggest where more careful attention and effort should be focused. Listed below are cases that were considered in the sensitivity analysis of the base-case utility function.

Because potential fatalities are very important, the linearity of the component utility function for fatalities was relaxed, and a risk-averse utility function was used over its range. In this case, since preferences decrease as the level of the performance measure increases, the constantly-risk-averse utility function

$$u(x) = h - be^{cx} \quad \text{(G-20)}$$

is used for performance measure X, where h is a constant and b and c are positive constants. The constants h and b are included to scale the component utility from 0 for the worst level to 1 for the best level of the performance measure.

The implications of a risk-prone utility function for fatalities that promotes ex-post equity were also examined. The component utility function used in this case was the constantly-risk-prone utility function

$$u(x) = h + be^{-cx} \quad \text{(G-21)}$$

where all of the constants have the same interpretation as in Equation G-20.

It seemed appropriate to vary the form of the utility function to examine the possible implications of overall risk attitudes quite distinct from the base case. To see how this can be done, recall that the base-case utility function u is also a measurable-value function. As a measurable-value function, u combines the impacts on all the performance measures into one numerical "measurable value." The base-case utility function is risk neutral, implying that a lottery with a 0.5 chance of an impact with a measurable value of 90 and a 0.5 chance of an impact with a measurable value of 10 is indifferent to an impact with a measurable value of 50 (i.e., the average of the lottery). If the sure impact with the 50 measurable value is preferred to the lottery, then a risk-averse attitude is implied. On the other hand, if the lottery is preferred to the impact with a measurable value 50, a risk-prone attitude is implied. Both of these possibilities can be investigated by assuming that the utility function is an exponential function of the measurable value, designated u, so that

$$U(x_1,\ldots,x_{14}) = A + B \exp[cu(x_1,\ldots,x_{14})], \quad \text{(G-22)}$$

where A and B are constants to set the range of U equal to that of u (see Keeney and Raiffa (1976) and von Winterfeldt and Edwards (1986)). The constant c indicates the risk attitude; it is positive for risk-prone utility functions and negative for the risk-averse utility functions. The greater the magnitude of c, the greater the aversion or proneness to risk.

Ranges of the different value tradeoffs were important to consider. As an example from the preclosure analysis, the base-case value tradeoff between performance measures X_1 and X_{13} indicated that the relative value assigned to one statistical radiological fatality in a repository worker was as undesirable as an additional cost of 1 million dollars. The range for this value tradeoff in the sensitivity analysis went from 1 to 25 million dollars. In the composite analysis, sensitivity analyses varied the relative weights on the preclosure and the postclosure implications of the various sites. This was done by varying the weights k_{pre} and k_{post} in Equation G-19. Since this seemed to be a potentially crucial value tradeoff, the sensitivity analysis considered the entire range of from 0 to 1 for each of the scaling factors, keeping the constraint that they must sum to 1.

G.4 APPROPRIATENESS OF THE UTILITY FUNCTION

In this section, the appropriateness of the utility function for evaluating the nominated sites is appraised. Specifically, succinct comments are provided on the reasons for the fundamental values that comprise the multiattribute utility function.

G.4.1 THE SET OF OBJECTIVES

The set of objectives chosen for a given problem collectively describes the consequences of major interest. Judgments are made about which objectives to include in the analysis and which to exclude. The intent is to include all the objectives felt to be useful for gaining insights from the decision-aiding methodology. The potential implications of any objectives not explicitly included in the study should be explicitly examined, at least qualitatively, in a sensitivity analysis and appraisal of the results of the analysis.

The major concerns in this problem were health-and-safety, environmental, socioeconomic, and cost impacts, and these concerns are explicitly addressed. With regard to health-and-safety impacts, the main distinction is between those occurring in the preclosure period and those occurring after closure. Furthermore, in the preclosure period, distinctions are made between health-and-safety effects on waste-management workers and effects on the public and whether the health-and-safety impacts result from radiological causes or nonradiological causes like traffic accidents. Collectively, the objectives address the major concerns raised in the DOE's siting guidelines (10 CFR Part 960).

Objectives not explicitly included in the study include nonfatal health-and-safety effects, socioeconomic impacts in regions through which the waste will be shipped, equity considerations (e.g., the equity of the risk to beneficiaries of nuclear power and to others living in different States), and political considerations. With regard to nonfatal health-and-safety effects, it is expected that these are highly correlated with the fatal health-and-safety effects, and hence placing a greater weight on those performance measures could, in a sensitivity analysis, examine whether the inclusion of nonfatal effects might make a difference in the evaluation of the nominated sites. With regard to the socioeconomic impacts of waste transportation, equity, and political implications, it was felt that the range of these impacts is not likely to be significant enough to lead to different implications of the evaluation of the five sites, even though the absolute level of such impacts may be important. To place this latter statement on a more common basis, consider an individual who is about to purchase a new house. Although the individual may feel that cost of the house is important, it is not particularly relevant to the choice of the best house if the range of costs for all houses is small (e.g., within 2,000 dollars) relative to the range of the other important attributes in the choice (e.g., the quality of the local school system, distance from work).

The set of objectives is composed exclusively of fundamental objectives. Stated in another way, none of the objectives concerns means, which may be important, only for their implications on fundamental objectives. This allows one to evaluate alternatives in terms of what is fundamentally important. It avoids many of the possibilities of double counting consequences, and it increases the understanding of the analysis. For instance, there is no fundamental objective that states that the purpose is to minimize the radiation emitted during the transportation of spent fuel to the repository. This is of course very important, but it is important only because it is a means to the potential radiological health effects that may eventually result from such emissions. Since the fundamental health effects are included as objectives, there is no reason to include the means objectives of radiation emitted.

G.4.2 THE SET OF PERFORMANCE MEASURES

The performance measures in the preclosure analysis are designed to indicate the direct interest with respect to the given objective. For instance, since one is concerned with radiological health effects, the performance measure is the number of fatalities. This should be contrasted with what is commonly used in many analyses--namely, a proxy performance measure. For instance, in this case, a proxy measure might be the radiation dose received by people. Such proxy measures are difficult to interpret for all but experts in the given field and require a translation from levels of the proxy measure into the fundamental concern. Specifically, it is necessary to have some idea about how a radiation dose is related to a specific number of cancer fatalities. The preclosure analysis makes such implicit translations unnecessary by carefully defining direct performance measures. The postclosure analysis, partially because of the extremely long period of concern, does use proxy measures to indicate performance. The reasons for defining the performance measures as releases of radionuclides rather than health effects are discussed in Chapter 3.

It is not difficult to develop direct performance measures when the concern is with fatalities or costs. However, it is worthwhile to elaborate on the eight performance measures used for health-and-safety effects in the preclosure analysis. Specifically, it is informative to distinguish between the concept of a statistical fatality and an identifiable fatality. A short description may help define these terms.

Suppose that there is an accident in a coal mine and that one miner, named Paul Kring, is trapped in the mine. There is enough water and air for him to survive for a week, and a quick appraisal indicates that it would cost 10 million dollars to drill a special shaft and rescue Paul, an effort that is sure to be successful. A decision is made to proceed, and naturally almost everyone concerned believes that the decision is appropriate: 10 million dollars is certainly less significant than Paul's life. Just before the work begins, however, a person familiar with mine safety says the following: "Coal mining is clearly a risky occupation and from time to time there are accidents in the mine. These accidents are invariably due to weakened structural supports. If we spent the 10 million dollars to strengthen the support system, we could expect five fewer mining accidents over the next 10 years, and national records of fatalities in mining accidents suggest that the lives of six miners would be saved. Why should 10 million dollars be spent to save the life of one miner when the same amount could be spent to save six miners?"

Perhaps 10 million dollars should be spent for each of the purposes, but if only one of the purposes could be pursued, many persons would suggest rescuing Paul. There is, of course, no right or wrong answer to this question. Rescuing Paul is saving an "identifiable fatality." Saving six workers who would not be in accidents that do not occur would be avoiding six "statistical fatalities." In the former case, everyone knows who is saved, whereas in the latter case this is never known. Because of this distinction, it may be appropriate for the value tradeoff between costs and statistical fatalities to be smaller than the value tradeoff between costs and identifiable fatalities. In the analysis of repository sites, the types of fatalities being considered are statistical fatalities resulting from very small incremental risks to a large number of people.

There are no natural scales to directly measure that which is fundamentally important with environmental and socioeconomic consequences. Thus, groups of professionals were asked to define levels of the performance measures that could communicate potential implications with regard to the respective objectives of siting a repository at the different sites. Again, the strength of this approach is that it makes the judgments used in the study explicit, and it attempts to clearly communicate the reasoning behind those judgments. Furthermore, it assists in differentiating professional judgments about the level of impacts from value judgments about the relative importance of those different levels of impacts.

G.4.3 THE ADDITIVE UTILITY FUNCTION

Whenever the objectives in the given problem context are fundamental and measured by direct performance measures, there is a sound basis for an additive utility function (see Keeney, 1981). For instance, if the additivity assumption did not hold between cost performance measures and fatality performance measures, it would imply that the amount of money one would be willing to expend to reduce the number of fatalities from 10 to 5 would be different from the amount of money one would spend to reduce the number of fatalities from 5 to 0. This would imply that one set of five potential statistical fatalities was more important that another set of five statistical fatalities, which seemed inappropriate. It may be argued that it might be politically more important to reduce fatalities from 5 to 0 than from 10 to 5, but the purpose of the assessments was to help identify the sites to be recommended for characterization, and not to minimize some adverse political implications to the government, to the DOE, or to the nuclear program.

G.4.4 LINEAR COMPONENT UTILITY FUNCTIONS

The linear utility functions for the health-and-safety and cost performance measures indicate that a given unit change in any of those performance measure is equivalent in value to any different unit change on that same performance measure. In other words, with regard to each fatality performance measure, the third statistical fatality must be considered as important as the ninth statistical fatality. This value judgment seems appropriate for three reasons: (1) a given probability of any individual's loss of life should be evaluated equally regardless of whether 0 or 10 other individuals have died from the same cause, (2) the linear utility function is consistent with minimizing the number of lives lost for any given investment of funds (see Keeney 1985), and (3) even if the worst end of the ranges of all fatalities occurs, these represent small amounts relative to the 50,000 traffic deaths and over 350,000 cancer deaths per year, and hence is not analogous to a large-scale catastrophe, where risk aversion may be reasonable (see Nichols and Zeckhauser, 1985).

The linearity assumptions about cost seemed appropriate, since the costs would be distributed over millions of persons through the fee levied on nuclear utilities for electricity generated with nuclear fuel. Since such cost would not likely be a major portion of the budgets of any of those citizens, the linearity assumption seems quite reasonable.

G.4.5 VALUE TRADEOFFS AMONG DIFFERENT PRECLOSURE STATISTICAL LIVES

The performance measures concerned with preclosure statistical lives are those designated X_1 through X_8. They differentiate fatalities into those related to workers and the public, those induced by the repository and by transportation, and those induced by radiation and other causes, such as traffic accidents.

One value judgment explicitly built into the multiattribute utility function was that a radiological or nonradiological fatality in a worker or a member of the public should not differentiate as to whether the fatality is attributable to the repository or to transportation. Thus, for instance, the death of a transportation worker in a traffic accident was considered as important as the death of a mine worker constructing the repository. Similarly, the radiological death of a member of the public was considered equally important, whether that fatality is attributable to the repository or to transportation.

A separate value judgment was made that the base-case utility function should evaluate a radiological fatality in a worker as equivalent to a nonradiological fatality in a worker. There were balancing reasons for this judgment. It was felt that in general a radiological fatality, which results from cancer, is more dreaded by citizens in our society, and hence it should have a greater weight. On the other hand, the average cancer-induced fatality usually occurs later in an individual's life than the average construction or transportation accident. Hence, there is a greater loss of life expectancy from a nonradiological fatality than a radiological fatality. This tends to suggest that the relative importance of the nonradiological fatality is greater than that of a cancer fatality. It was felt for the base-case evaluation that these two considerations would roughly balance each other, and hence the relative significances of a nonradiological and a radiological were considered equivalent. This was the case both for workers and for members of the public.

A judgment was necessary about the relative importance of the death of a member of the public and of a waste-management worker. Although clearly both fatalities are extremely important, it was judged that a public fatality was considered a greater loss to society. This is because it is generally understood that all types of work have associated risks and that the individuals performing that work are doing so voluntarily and to some extent are compensated for those risks. On the other hand, members of the public are not compensated and are not necessarily willingly involved in waste-management. The distinction is sometimes referred to in the technical literature as a fatality due to a voluntarily accepted risk for the workers and due to an involuntarily accepted risk for members of the public (see, for example, Starr 1972). It was decided that the base-case evaluation should consider the death of a member of the public four times more important than the death of a worker. This ratio was partly due to the fact that current regulations allow the radiation exposures of workers to be 10 times greater than the exposures of members of the public. However, the dose received by workers is monitored very carefully so that actions can be taken if the dose is near the dose limit. Thus, the ratio of 10:1 implied by the regulations for the relative importance of public fatalities to worker fatalities was reduced to 4:1 because of the ability to take action to avoid additional radiation exposure of workers when this seemed appropriate.

G.4.6 VALUE TRADEOFFS BETWEEN COSTS AND PRECLOSURE STATISTICAL LIVES

Perhaps the most important value tradeoff in this study involves that between costs and statistical lives. In particular, let us consider the value tradeoff between costs and statistical public fatalities. Several specific questions may be appropriate.

First, one might ask why the construction and operation of a repository cannot be completely safe such that no members of the public have any risk of losing their lives. The same question might indeed be asked with regard to workers. The simple answer is that, though safety-and-health consequences are extremely important, there is always the chance that fatalities will occur. Actions should be taken to minimize these to the extent practicable. Indeed, by explicitly addressing the value tradeoff between costs and statistical lives, the concept of "to the extent practicable" is made operational. However, it is clear that there is always the possibility of accidents in mines and of traffic accidents, both of which may result in the deaths of workers. Furthermore, traffic accidents could lead to fatalities in members of the public, which is unfortunately all too well understood by the citizens in our country. Furthermore, nuclear material does emit radiation, which can cause cancers that may be fatal.

It might be stated that it is immoral to trade off lives, even when they are statistical lives, against costs. The fact is that the nature of the problem requires such a tradeoff. The main issue is whether this value tradeoff is made explicitly or implicitly. Many moral theories hold the value of a life to be of paramount importance, and actions that are not made to save lives where possible are deemed immoral. To the extent that analysis can help lead to better decisions and result in the savings of more lives, it is perhaps immoral not to explicitly address the crucial value tradeoffs between costs and statistical fatalities (see Keeney, 1984).

The fundamental question is, Why is a value tradeoff of 4 million dollars per statistical life reasonable for this analysis? Part of this answer lies in what actions might be taken if that money were not expended. If 4 million dollars was not expended, it would remain in the hands of individual citizens (i.e., those paying nuclear utilities who pay waste-disposal fees), or it would used by government for other purposes. If used by government for other purposes, as shown by Graham and Vaupel (1981), there are many government programs where statistical lives can be saved for significantly less than 4 million dollars. In fact, it has often been argued that as a society we can save deaths on the highways from expenditures much smaller than a million dollars (see Cohen, 1980, 1983). Since most of the public fatalities due to the repository are in fact highway fatalities, it seems inappropriate to spend significantly more than a million dollars on improving spent-fuel transportation to save public lives on the highway when we could save more lives for the same expenditures directly on highway improvements. And it is important to recognize that the individuals at risk in both of these cases are precisely the same--namely, the people driving on highways.

If the 4 million dollars is not used by the government for safety purposes and remains in the hands of individuals, these individuals have the option of using their funds to enhance either their safety and health or the quality of their lives in other ways. Some of these funds may be spent for health care, for home fire alarms, for automobile-safety equipment, or for nutrition. Cohen (1980, 1983) calculates that many individual options of screening for cancer can save lives at a present cost of less than a million dollars. Indeed, it has been persuasively argued by Wildavsky (1980) that richer is safer. In addition, Keeney and von Winterfeldt (1983) discuss many pathways that lead to public fatalities when the costs of regulations that increase electricity prices are passed on to consumers.

One additional guideline for the value of a statistical public life is provided by the Nuclear Regulatory Commission in 10 CFR Part 50, Appendix I, which states that a sufficient condition for determining whether risks to the public are as low as reasonably achievable is to make investments that require up to 1,000 dollars for each man-rem of avoided population dose. This guideline presumably takes into account both fatal and nonfatal effects of such radiation. If it is considered only for the fatal effects, then using the dose-response that 280 fatal cancers are caused by every million man-rem of radiation dose, it can be calculated that a fatality is deemed equivalent in significance to the cost of 3.6 million dollars.

Concerning statistical worker fatalities, Thaler and Rosen (1976) examined what additional premiums in pay were necessary to induce individuals to engage in riskier occupations (e.g., mining). They found that $200 per year was required to accept an increase of .001 in the annual probability of accidental death. From this, a value tradeoff of $200,000 to avoid a statistical worker fatality was calculated. Rappaport (1981) using different data and procedures, derived an analogous value tradeoff of 2 million dollars.

Because of the generally acknowledged significance of fatalities and because the Nuclear Waste Policy Act clearly states the paramount importance of potential fatalities for evaluating repository sites, the base-case value tradeoffs were chosen as follows: 4 million dollars is indifferent to one statistical public fatality and 1 million dollars is indifferent to one statistical worker fatality. Sensitivity analyses investigated the implications of increasing these up to 25 times.

G.4.7 VALUE TRADEOFFS BETWEEN COSTS AND ENVIRONMENTAL AND SOCIOECONOMIC IMPACTS

As is clear from Table G-6, if the three environmental performance measures were at their worst level, and the socioeconomic performance measure was at its worst level, it would be more important to completely alleviate the socioeconomic impacts. Specifically, this would be worth 500 million dollars. To alleviate the aesthetic impacts associated with the worst level would be worth 100 million dollars. To eliminate the biological impacts associated with the worst level would be worth 30 million dollars, and to eliminate the archaeological impacts associated with the worst level would be worth 20 million dollars. As discussed in Section G.3, this does not generally imply, for instance, that aesthestic impacts are more important than biological impacts. It implies that the specific range of aesthetic impacts represented by the performance measure for this problem is more important than the specific range for the biological impacts represented by the performance measure for the problem. It was felt that the socioeconomic impacts associated with the worst level could cause significant changes in the local social and economic conditions. If, for instance, the area surrounding a repository site had approximately 50,000 people and sustained this major socioeconomic impact, the 500-million-dollar value tradeoff would be equivalent to 10,000 dollars spent to avoid that impact on each of those persons.

With regard to aesthetic impacts, the major ones would concern the degradation of visual vistas and potentially annoying noises in otherwise serene or rural settings. It is noteworthy to recognize that these implications, though important, do not last forever and end when the repository is closed and decommissioned approximately 70 years after opening.

For instance, if 300,000 people visited a particular site known for its vista in each of 30 years, the 100-million-dollar value tradeoff would be equivalent to approximately 10 dollars per person for the inconvenience or disappointment about having the vista somewhat degraded.

The 20-million-dollar and 30-million-dollar value tradeoffs for archaeological and biological impacts are much smaller than those of the aesthetic impact mainly because of the range involved. With archaeological impacts, this is equivalent to 5 million dollars spent to avoid major adverse impacts on a historical property of major significance, and the 30 million dollars to alleviate biological impacts is spent to avoid a threat to the regional abundance of either threatened or endangered species and biologically sensitive species. However, this threat would not concern the national abundance of those species.

G.4.8 VALUE TRADEOFFS BETWEEN PRECLOSURE AND POSTCLOSURE STATISTICAL LIVES

A unique aspect of a geologic repository is that the health implications could occur over thousands of years. There was little available guidance to establish a value tradeoff between preclosure statistical fatalities and postclosure releases of radionuclides, which can result in postclosure statistical fatalities. Fortunately, perhaps, the postclosure analysis had similar implications over the extremely wide range of value tradeoffs where a postclosure fatality was evaluated equivalent to more than 350 preclosure fatalities or equivalent to a very small risk of one fatality in the preclosure period.

It is useful to point out that a willingness to tradeoff multiple deaths in the future to avoid one death today does not imply that our generation considers the lives of members of future generations less significant than present lives. Such a value tradeoff reflects a value judgment that it is reasonable and responsible to spend more current funds to save 10 lives in the current generation than to save more than 10 lives in 5000 years. This view would be consistent with "discounting" future life in the analysis. A quote from Raiffa et al. (1978) illuminates the fundamental logic of discounting possible future losses of life:

"This discounting is merely an accounting device to place the dollars spent and the lives saved at the same point in time. In effect, we discount future lives precisely because dollars invested today should be expected to yield more life-saving in the future than in the present. It is because of our concern that resources be applied at the point in time where they can save the most lives that we discount lives. It is, emphatically, <u>not</u> because we wish to value future lives less than we value present lives in any absolute or utilitarian sense. It is because we do not want to be wasteful of scarce resources in saving lives, either present or future."

G.5 CONSISTENCY OF THE UTILITY FUNCTION WITH THE SITING GUIDELINES

The implementation guidelines of the DOE siting guidelines contain statements that can be used as guidance for the specification of the utility function to be applied in a multiattribute utility analysis of the nominated sites. Specifically, the guidelines contain statements that might be regarded as bearing on the scaling factors for evaluating preclosure versus postclosure repository performance and preclosure performance in various areas. Among the relevant statements are the following:

1. "Evaluations of individual sites and comparisons between and among sites shall be based on the postclosure and preclosure guidelines."

2. "Evaluations shall place primary significance on the postclosure guidelines and secondary significance on the preclosure guidelines."

3. "Preclosure guidelines contain technical guidelines separated into three groups that represent, in decreasing order of importance, preclosure radiological safety; environment, socioeconomics, and transportation; and ease and cost of siting, construction, operations, and closure."

4. "Comparisons between and among sites shall be based on the system guidelines to the extent practicable and in accordance with the levels of relative significance specified above for the postclosure and preclosure guidelines to the extent practicable and in accordance with the levels of relative significance specified above for the postclosure and the preclosure guidelines."

5. "If the evidence for the sites is not adquate to substantiate such comparisons, then the comparisons shall be based on the groups of technical guidelines, considering the levels of relative significance appropriate to the postclosure and the preclosure guidelines and the order of importance appropriate to the subordinate groups within the preclosure guidelines."

With regard to statement 1, the multiattribute utility analysis of the sites is indeed based on the postclosure and preclosure guidelines. As explained in the main text, the site-selection objectives established for the analysis are based on the intent of the qualifying conditions of the system guidelines, and the performance measures were systematically related to key factors of the technical guidelines, as demonstrated by the various influence diagrams in Appendixes B and E. The multiattribute utility analysis essentially integrates the considerations inherent in the system and technical guidelines in a way that logically accounts for the complex relationships and interactions that are important to a comparative evaluation.

Qualitative statements about relative significance and importance are imprecise. Therefore, it is not possible to translate the above-cited statements about significance and importance into precise quantitative values for the scaling factors or for the value tradeoffs that such scaling factors imply. If the implementation guidelines had required that "sole significance" or "complete importance" be assigned to any one set of guidelines, then scaling factors could be selected to assign 100 percent of the weight to the objectives corresponding to these conditions and none to all others. Since the guidelines do not contain such statements, it is necessary to make judgments in trading off performance in one category against performance in another. For example, from the wording of statement 2 above it seems reasonable to conclude that if site A is estimated to produce only very slightly higher postclosure radionuclide releases than site B but entails considerably more preclosure radiological fatalities, much higher environmental and socioeconomic impacts, and much higher economic costs, then site B would be preferable. Similarly, establishing an order of importance for preclosure considerations does not imply that very small differences in the most important consideration should always overshadow large differences in conditions of lesser importance. The exact relative significance that should be assigned to differences in the estimated abilities of the sites to meet various objectives (which are specified by the numerical values for the scaling factors) cannot be derived from statements about primary significance or order of importance.

To ensure that postclosure is given primary significance, a complete sensitivity analysis of postclosure and preclosure scaling factors was conducted. The relative scaling factors assigned to preclosure and postclosure performance were varied across the entire range of possibilities (0 to 100 percent of the weight to postclosure), where all possible interpretations of primary significance are represented by some combination of weights. The ranking of the sites remains the same over most of the range. To change the ranking, it is necessary to use scaling factors that place an extremely low relative importance on preclosure performance. As indicated in Chapter 5, a conservative analysis (which is likely to overestimate the numbers of postclosure fatalities) suggests that one postclosure statistical fatality would have to be valued at least as highly as 10 and perhaps as highly as 350 preclosure statistical fatalities to justify scaling factors that would alter the base-case rankings of the sites. The DOE does not believe that such extreme views are a reasonable basis for conducting a comparative evaluation and does not regard such value tradeoffs as being required by its siting guidelines. If such an extreme view were adopted, the sensitivity analysis indicates that the sites would be judged essentially equally desirable, with Hanford just discernibly less favorable than the others.

To ensure that the analysis is consistent with the order of importance specified for preclosure impacts, three steps were taken. First, conservatism was introduced into the estimation of preclosure impacts as specified by the order of importance. The most conservative analysis was used for the estimation of radiological-safety impacts. For example, the dose-effect relationship used in the estimation of radiological health effects is 280 fatalities per million man-rem. A recent analysis prepared for the Nuclear Regulatory Commission (NRC, 1985) proposes a risk factor of 190 fatalities per million man-rem. This estimate, derived by methods similar to those employed by the National Academy of Sciences in the BEIR Report (NAS, 1980) but with the benefit of more recent information, agrees with many earlier estimates. Despite the evidence supporting lower risk factors, the higher factor was selected as the basis for the preclosure analysis to reflect the importance of preclosure radiological safety. In the case of environmental and socioeconomic impacts, base-case estimates were intended to be best judgments. In the case of costs, however, base-case estimates may understate the potential for higher costs. Estimates of total repository costs have increased significantly in recent years, and experience demonstrates that large construction projects more often than not exceed cost projections because of delays, changing requirements, legal circumstances, and other unexpected conditions. Although the DOE recognizes these realities, such considerations were not used to increase the estimates of costs in the analysis.

Another step adopted to meet the order-of-importance requirement involved the base-case scaling factors used in the preclosure analysis. In effect, the requirements of the guidelines led to the adoption of scaling factors for radiological impacts that are somewhat higher than those that would have been selected in the absence of the guidelines. Similarly, the scaling factors for the ease and cost of siting, construction, operation, and closure are somewhat lower than they would otherwise be. The basis for these judgments is discussed in Section G.4 of this appendix.

A third important step adopted to meet the order-of-importance requirement for preclosure performance was to conduct a thorough sensitivity analysis to investigate whether changes in the value tradeoffs would alter conclusions. As described in Chapter 4, the sensitivity analysis greatly increased the relative values assigned to radiological safety and to environmental, socioeconomic, and transportation impacts. The basic implications of the analysis and the preclosure rankings are not sensitive to these changes. Therefore, the analysis is consistent with a broad range of interpretations regarding the relative importance of preclosure-impact categories.

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Appendix H

DOE INTERACTIONS WITH THE NATIONAL RESEARCH COUNCIL'S BOARD ON RADIOACTIVE WASTE MANAGEMENT

Appendix H

DOE INTERACTIONS WITH THE NATIONAL RESEARCH COUNCIL'S BOARD ON RADIOACTIVE WASTE MANAGEMENT

Between the publication of the draft environmental assessments (EAs) in December 1984 and this report, four meetings were held between the Department of Energy (DOE) and the Board on Radioactive Waste Management (BRWM) of the National Academy of Sciences-National Research Council. The purpose of the first meeting, held on March 22, 1985, in Augusta, Georgia, was to discuss the three aggregation methods used for comparative site evaluations in Chapter 7 of the draft EAs. As a follow-up to that meeting, in a letter dated April 26, 1985, the BRWM said, among other things, that "the methodology of comparative assessment is unsatisfactory, inadequate, undocumented, and biased and should be reconsidered...."

In addition to these comments by the BRWM, numerous comments from the public and other interested parties addressed the site comparisons in Chapter 7 of the draft EAs. In response to the comments, the DOE conducted, from June through August 1985, a preliminary study of a formal decision-analysis methodology for site comparisons. This study was performed by three of the people in the methodology lead group (Appendix A) and incorporated technical and value judgments from a few technical specialists. After a review of the study by DOE management, the Director of the Office of Civilian Radioactive Waste Management decided (1) to adopt the methodology used in the preliminary study as the methodology for aiding in the site-recommendation decision, and thereby involve a much larger number of technical specialists in its application, and (2) to seek outside review of the adequacy of the methodology. In a letter dated August 29, 1985, the DOE requested that this independent review of the methodology be conducted by the BRWM. The BRWM agreed to perform the independent review, and, as discussed below, the remaining three meetings between the DOE and the BRWM concerned the development and application of this methodology.

In September 1985, the DOE transmitted for review by the BRWM a generic description of the revised methodology. The DOE met with the BRWM on October 1-3, 1985, in Menlo Park, California, to discuss the methodology. On October 10, 1985, the BRWM sent the DOE a letter that generally endorsed the choice of the multiattribute utility method, but urged that its implementation be also subjected to an independent review. In a letter dated October 21, 1985, the DOE agreed to consider the recommendations of the BRWM and, subsequently, in a letter dated October 30, 1985, asked the BRWM to act as the independent reviewer of the implementation. Having been advised that the BRWM agreed to perform this independent review, the DOE in a letter dated November 6, 1985, scheduled two review meetings with the BRWM in December 1985 and January 1986. The latter meeting was subsequently rescheduled for March 1986.

On December 5, 1985, the DOE transmitted available materials on the actual implementation of the methodology, and on December 12-15, 1985, the DOE met with the BRWM in Washington, D.C., to discuss these materials. The BRWM was generally pleased with the direction of the analysis, but was unable to do a thorough review because the level of documentation was inadequate.

On March 17, 1986, the DOE transmitted a substantially complete report that documented the implementation of the methodology. On March 24-25, 1986, the DOE met for the last time with the BRWM in Washington, D.C., to discuss the contents of the report. In a letter dated April 10, 1986, the BRWM indicated general satisfaction with the implementation of the methodology for comparative evaluations of the nominated sites.

In its letter of April 10, 1986, the BRWM refers to the CSRR, or the Candidate Site Recommendation Report, and to a Chapter 6 that was to be a part of the CSRR. After the March 24-25, 1986, meeting with the BRWM and before receiving the BRWM letter, the DOE decided that the title of this report should be changed from the CSRR to the present title and that this report would serve to support the actual recommendation report from the Secretary of Energy to the President. There are several practical reasons for this change. Because of the size (nearly 500 pages) and technical detail of this report, and its basic purpose of establishing an initial order of preference for sites for characterization, it is more appropriate to present the final order of preference in a separate report. The recommendation report is considerably more concise and explains the basis for the final order of preference. This basis includes the results of this report together with the host-rock diversity requirements of the DOE siting guidelines (10 CFR Part 960, Subpart B) and other information. The other information was originally intended for the Chapter 6 referred to above, but it has since been incorporated into the recommendation report.

For the convenience of the reader, the correspondence between the DOE and the BRWM is reproduced in the attachment to this appendix.

Attachment to Appendix H

CORRESPONDENCE BETWEEN THE DOE
AND THE BOARD ON RADIOACTIVE WASTE
MANAGEMENT OF THE NATIONAL
RESEARCH COUNCIL

NATIONAL RESEARCH COUNCIL

COMMISSION ON PHYSICAL SCIENCES, MATHEMATICS, AND RESOURCES

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OFFICE LOCATION:
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April 26, 1985

Mr. Ben Rusche, Director
Office of Civilian
Radioactive Waste Management
RW-1/Forrestal
U.S. Department of Energy
Washington, D.C. 20585

Dear Mr. Rusche:

The Board on Radioactive Waste Management has reviewed Chapter 7 of the Draft Environmental Assessments (DEA's) that were issued in December 1984 by the Department of Energy (DOE) in response to Section 112 of the Nuclear Waste Policy Act (NWPA) of 1982. The chapter is seen to be particularly important because in it DOE presents a comparative evaluation of the five sites under consideration for site characterization. The characterization step, which will require constructing a shaft and conducting explorations at repository depth, is then proposed for three of the sites -- Deaf Smith, Texas (in bedded salt); Hanford, Washington (in basalt); and Yucca Mountain, Nevada (in tuff) -- which is the minimum number required by the act.

As a preface to its comments, the Board would like to compliment DOE for issuing the Environmental Assessments in draft form for public comment, which is not required by the act. While this letter offers a number of recommendations for possible improvement, the Board recognizes that DOE has had to comply with the final General Guidelines for the Recommendation of Sites (published in the Federal Register in December 1984), and that the decision being addressed by the DEA's is strictly on which of the sites to concentrate the necessary further study. The characterization step, which will require spending hundreds of millions of dollars at each site, will clearly provide much more data than is known at present, and ultimately the information on which to base the eventual decision on where to site a repository.

The Board's criticism of the Draft Chapter 7 and Appendix B is focused on three major concerns:

- The methodology of comparative assessment is unsatisfactory, inadequate, undocumented, and biased and should be reconsidered in accordance with the following paragraphs;
- Insufficient weight and attention are placed on the clear need to find a site <u>adequate</u> under the <u>post-closure</u> guidelines before considering its relative rank under <u>pre-closure</u> guidelines; and

- Quite apart from the question of technical acceptability, the presentation of the methodology of comparison is sufficiently important that it should be highlighted as a stand-alone issue separate from the earlier parts of Chapter 7 which speak to site suitability.

The comparison process used by DOE was, first, to rank the five sites for each of the twenty technical guidelines, and then to aggregate the rankings by three simple quantitative methods. The Board does not consider the "averaging method" and the "pair-wise comparison method" to be satisfactory since the spread in rankings is artificially determined. The "utility estimation method," or multiattribute analysis, can be a valid means for comparing sites based on the eleven pre-closure guidelines (which deal with radiological safety; environment, socioeconomics, and transportation; and ease and cost of construction, operation and closure).

However, since multiattribute analysis is a technique that is appropriate and useful only when other analytic comparisons cannot or can no longer be made, the application of this method to the post-closure guidelines is not an adequate means of assessing repository performance. Many of the post-closure factors, such as the ones dealing with geohydrology, geochemistry, rock characteristics, and dissolution, do not act independently in determining performance, and their relative importance is site-specific. The DOE method treats the factors independently and gives them equal weights for all the sites. For the post-closure guidelines, the Board recommends a different method of assessing performance, which does not use multiattribute analysis except as a way to estimate qualitatively the uncertainties.

In carrying out the analysis for both the post-closure and pre-closure factors, it is necessary to make clear how the ratings of the sites for each factor are determined and by whom. The same can be said for the weightings given each factor. A series of expert panels of judges is needed in order to have a measure of the variability of the ratings and weights, which can then be used to assess the stability of the final rankings. The DOE analysis did not make clear who assigned the ratings or the weights. One procedure might be to use the combined group of technical review committees as mentioned in the discussion of post-closure performance assessment below to reassess the ratings for each site for each guideline, as a basis for an evaluation of the sensitivity of the overall rankings to these individual ratings. Finally the Board questions the DOE assumption that lack of information should be equated with unfavorable information in rating a site for a particular factor. For example, the lack of information on the ability of the Department of Energy to acquire the Utah site, which is now owned by the U.S. Government but controlled by the Bureau of Land Management, resulted in the very low ranking on ownership.

Of far greater importance than the premature use of multiattribute analysis, the DOE weighting of the post-closure and pre-closure factors (51:49, respectively) seems to be biased too much towards the latter, and barely in keeping with the requirements of the guidelines. (The Board recognizes that DOE did vary the overall weighting between the sets of pre- and post-closure factors.) The post-closure guidelines are clearly the most important and the adequacy of a site under the post-closure guidelines must be clearly established before attempting comparison with other sites. Deficiencies in the pre-closure factors can be mitigated substantially at increased cost.

The Post-closure comparison methods used by DOE, and quite possibly the method recommended by the Board, do not discriminate significantly among the sites. Consequently, the choice of sites for characterization is driven largely by the variances in the ratings of the pre-closure factors. This very important feature of DOE analysis should be clearly stated in Chapter 7 and highlighted for the reader.

A scientifically defensible method for integrating and properly weighting the post-closure factors at each site is to conduct a "performance assessment", such as was advocated in the Research Council's WISP Report*, using analytic models. With adequate data and confidence in the models, the performance assessments could then be used to compare sites. Even with the current uncertainties and the variability in the quantity and quality of data, performance assessments are still a better means to compare sites for the post-closure guidelines than the method used by DOE. The use of performance assessments is compatible with the system requirements of the final Guidelines, and the Board urges consideration of the methodology advocated in the WISP Report. The Board recognizes, however, that although performance assessments using the current state of knowledge may be able to establish adequacy with respect to post-closure guidelines, they may not be able to discriminate among the five sites assessed to achieve a clear ranking: one site may have lower average releases but a higher variance in the estimate than another site.

Any attempt to rank sites based on the post-closure factors would require a measure of confidence in the magnitude of the uncertainties in the performance assessments. Because the probability distributions for many of

*Waste Isolation Systems Panel, Board on Radioactive Waste Management, Commission on Physical Sciences, Mathematics, and Resources, National Research Council "A Study of the Isolation System for Geologic Disposal of Radioactive Wastes" National Academy Press, Washington DC 1983. See Chapter 9.

the factors that enter the assessments are poorly known at this time, purely analytic methods cannot be used. In this case, multiattribute sensitivity analysis could be used to estimate qualitatively and subjectively the degree of confidence in the performance assessments. For example, the assessments could be used to identify the factors that would appear to be most important for a particular site and the conditions that, if they occur, would compromise performance. A group of experts could then be used to rate and rank the sites based on their current degree of confidence (in terms of an estimated probability) that the unfavorable conditions will not occur and that the repository performance will be better than a specified level. This comparison method will subjectively take into account the different quantities and qualities of data at the sites and the uncertainties in modeling, and it will focus attention on the most serious potential problems as well as the most favorable characteristics for each site. The sites could also be rated and ranked on the basis of an expert group's assessment of the likelihood that characterization will satisfactorily resolve outstanding issues and uncertainties to the degree required for licensing by the Nuclear Regulatory Commission.

If DOE should wish to use this comparison method in the near term, there is a knowledgeable group that could be assembled quickly. The combined group of technical review committees for all of the sites could be brought together and given the tasks outlined above. It would be instructive to see how much agreement (and variability) would emerge when this group attempted to assign a degree of confidence to each of the performance assessments.

More generally, the Board believes that pooled judgement by knowledgeable experts is an appropriate means to assess uncertain and incomplete technical information. The fragile character of these peer judgements is reflected in the fact that how one poses the questions to be answered can affect the outcome. The Board has no expertise to offer on the cognitive psychology of eliciting peer judgements, but it does seem clear that both the range of uncertainty in data and the uncertainties in the models that analyze those data should be assessed.

The Board recommends that great emphasis be placed on learning from each step throughout the multi-year process of developing a repository. The characterization of several sites at repository depth is now needed for this learning process to continue. A question arises as to the best and most robust strategy if one or more sites should fall by the wayside during the characterization process. Clearly, if it were determined that three sites must be qualified after characterization in order to submit a license application to the NRC, then it would be prudent to characterize more than three sites. It is extremely important, therefore, for this issue to be resolved quickly. Even if three qualified sites are not required, the Board believes it is technically desirable and important to consider additional exploration at the two sites not currently recommended for characterization, although this may be difficult under the provisions of the Nuclear Waste Policy Act.

The Board's third major concern after pointing out the flaws in the method and the lack of emphasis on adequate site as against best site, is with the presentation of the method of comparison of the sites. Chapter 7 and Appendix B explain the method of selection of sites for characterization, but neither does that job adequately. The methodology of comparison (now Section 7.4) should, after revision, be given a position of greater emphasis by withdrawing it from Chapter 7 and making it a stand-alone issue. The most important points in the present methodology, such as the fact that the pre-closure ratings largely determine the final rankings, are not clearly and crisply stated. Critical information, such as the ratings given sites for various factors (Tables B-2 and B-3), should not be buried in an appendix. Explanations can be clear even when the comparison process is complicated.

The Board appreciates the difficulties involved in drafting Environmental Assessments and making a selection at this stage of the data collection and further appreciates the opportunity to comment on the Environmental Assessments. We wish you well in your task of making the necessary major revision, and would be pleased to amplify any of the points raised in this letter or in our recent meeting with OCRWM staff.

Sincerely,

Frank L. Parker

Frank L. Parker
Chairman

FLP:jc

Department of Energy
Washington, DC 20585

AUG 29 1985

Dr. Frank Parker
Vanderbilt University
P.O. Box 1596, Station B
Nashville, Tennessee 37235

Dear Dr. Parker:

This is in reference to your telephone conversation with Tom Isaacs of my office on August 5, 1985, regarding the possibility of the National Academy of Sciences'(NAS) Board on Radioactive Waste Management conducting an independent review of the methodology to be used to evaluate sites for consideration as candidate sites for characterization for the first geologic radioactive waste repository. We would like to request the Board's review consistent with the scope and schedule described below.

As outlined in the Department's siting guidelines for nuclear waste repositories (10CFR960), "[o]n the basis of the siting provisions specifying the basis for site evaluations in 960.3-1-5, the sites nominated as suitable for characterization shall be considered as to their order of preference as candidate sites for characterization" (S960.3-2-3). In the draft Environmental Assessments issued in December 1984, the Department included in section 7.4 of Chapter 7 a proposed order of preference of the proposed nominated sites based in part on several ways of combining site rankings under the individual guidelines. We have received a number of comments, including those of the Board, on the rankings and the methodology used in the draft EAs. In light of these comments and the concerns expressed by the States, the Department is reexamining the methodology used in the draft EAs to consider appropriate changes for the final EAs. Such a reexamination is now in progress. We believe that an independent review of ranking methodology by an organization such as the NAS Board would be useful in assuring an effective and credible document.

It is our understanding that the NAS Board on Radioactive Waste Management is willing to perform an independent review of the adequacy of a ranking methodology to be used in the final EAs scheduled for publication in December 1985. The Department would intend to append your review findings to the final EAs and to the Secretary's nomination and recommendation to the President. We can provide you with a copy of the ranking methodology to support development of the preferred order of sites at least two weeks prior to the next scheduled meeting of the Board on October 1-3, 1985. For the review findings to be appended to the EAs, we would need to receive the Board's letter report or other appropriate document by November 15, 1985.

We look forward to your reply. Should you accept our request for this important review of the ranking methodology on behalf of the NAS, please contact Tom Isaacs or me so that we may arrange to provide you with all the pertinent information in a timely fashion.

Sincerely,

Ben C. Rusche

Ben C. Rusche, Director
Office of Civilian Radioactive
Waste Management

cc: Peter Myers
National Academy of Sciences

cc. [handwritten]

NATIONAL RESEARCH COUNCIL

COMMISSION ON PHYSICAL SCIENCES, MATHEMATICS, AND RESOURCES

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August 30, 1985

Mr. Ben C. Rusche, Director
Office of Civilian Radioactive
Waste Management
U.S. Department of Energy
Washington, D.C. 20585

Dear Mr. Rusche:

This is in reference to your letter to Dr. Frank Parker, Chairman of the Research Council's Board on Radioactive Waste Management, dated August 29, 1985 requesting a review by the Board of the ranking methodology to be contained in the forthcoming Environmental Assessments. Dr. Parker has asked me to respond that the Board will be happy to undertake the review consistent with the scope and schedule described in your letter.

To accomplish the review within the specified time, it will be of great importance to have the referenced copy of the ranking methodology at the earliest possible time in order that Board members can have adequate opportunity to study it before the meeting. We understand from Tom Isaacs that we can expect to have it by or before noon on September 16th which will allow it to be duplicated and dispatched by express mail before the close of business that day. We will be in touch with Tom regarding details of the meeting and DOE resource persons attending it.

Sincerely,

Peter B. Myers [signature]

Peter B. Myers
Staff Director
Board on Radioactive
Waste Management

PBM:jc

cc: Frank L. Parker
Tom Isaacs

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October 10, 1985

Mr. Ben C. Rusche, Director OCRWM
U.S. Department of Energy
RW-1/Forrestal
Washington, D.C. 20585

Dear Mr. Rusche:

In response to your August 29, 1985 request that the Research Council's Board on Radioactive Waste Management conduct "an independent review of the methodology to be used to evaluate sites for consideration as candidate sites for characterization for the first geologic radioactive waste repository", the Board has reviewed the Department of Energy's (DOE) August 1985 document "A Methodology for Aiding Repository Siting Decisions." The document describes work in progress on the application of the multiattribute utility technique to help the Secretary of Energy select three sites to recommend to the President for characterization as candidate sites for a repository for permanent deep geologic disposal of high level radioactive waste as required by the Nuclear Waste Policy Act (Sec 112 (b) (1) (B)).

The Department of Energy's August methodology paper presents only the basic concepts of the multiattribute utility technique, together with a few simplified illustrative examples. Consequently, it is important to note that, except for some of those involved in multiattribute utility technique itself, the Board on Radioactive Waste Management did not have an opportunity to consider matters of technical substance, such as site-specific data or revisions to the draft Environmental Assessments. Further, since it was not contained in the methodology document, the Board was not able to examine the specific implementation of the multiattribute utility technique being developed by DOE (including performance measure scales, scoring procedures and associated probability distributions, influence diagrams, utility functions, weighting factors, and procedures for selecting panels of technical experts and DOE decision makers).

Nevertheless, the Board commends DOE for its adoption of a rigorous form of this decision-aiding methodology. While recognizing that there is no unique procedure for ranking, the Board believes that the multiattribute utility technique can be an appropriate method by which to integrate technical, economic, environmental, socioeconomic, and health and safety issues to assist DOE in its selection of sites for characterization. Thus we feel that our concern about the appropriateness of the methodology, as expressed in our April 26, 1985 critique of Chapter 7 of the December 1984 Draft Environmental Assessments, has now been addressed.

The National Research Council is the principal operating agency of the National Academy of Sciences and the National Academy of Engineering to serve government and other organizations

Although the multiattribute utility technique proposed by DOE appears appropriate, the technique must be implemented correctly and accurately to be useful and credible. The adequacy of the application of the technique can only be evaluated after the analysis is complete. In the absence of documentation on how the multiattribute utility technique is being applied by DOE we cannot now determine the extent to which our earlier concerns will be answered about the adequacy of site rankings, the appropriateness of documentation supporting and describing the results, and the potential for bias in applying the technique.

The multiattribute utility technique appears to be a promising approach for stating clearly and systematically the assumptions, judgments, preferences, and tradeoffs that must go into a siting decision. As explained in the Board's letter of April 26, 1985, the "utility estimation" technique used in Chapter 7 of the Draft Environmental Assessments was not adequate, because it treated post-closure factors independently and gave them equal weight for all sites. The Board reiterates that a scientifically defensible method of integrating and weighting the post-closure factors at each site is to conduct a "performance assessment" using quantitative models, as recommended in the National Research Council's report on the Waste Isolation Systems Project.

Were adequate data and validated models available, the results of the performance assessments could provide a direct estimate of post-closure performance, which could be integrated with pre-closure factors by using a multiattribute utility technique analysis to compare sites. When currently available performance assessments are not adequate for reliable direct comparison of the expected post-closure performance of the five sites, judgments of experts may be used to develop subjective estimates of the performance of the post-closure factors at each site. DOE has proposed that its technical experts and those of its contractors use this approach to develop performance measure scales and to score each site on those scales. The Board is concerned that DOE's use of its own technical experts to assess performance by this subjective method may mask the degree of real uncertainty associated with post-closure issues.

The Board believes that particular emphasis must be placed on the analysis and comparison of the post-closure performance of the sites in order to test the validity of the conclusion in the Draft Environmental Assessments that the five sites are essentially indistinguishable with respect to the post-closure measures. The credibility of those estimates would be substantially enhanced if an independent panel of outside experts were to review the complete analysis prior to issuance of the final Environmental Assessments.

DOE proposes to use multiattribute utility technique as a decision-aiding rather than decision-making technique. The Board on Radioactive Waste Management supports this limited approach. As stated in our letters of April 2, 1984 to DOE and the U.S. Nuclear Regulatory Commission, "The combination of complexity and uncertainty [in the repository siting problem] implies that DOE must be accorded substantial discretion to exercise its best technical judgment in recommending three of the nominated sites according to Sec. 112 (b) (1) (B)." Proper implementation of the multiattribute utility technique would illuminate DOE's decision process by presenting a comprehensive and explicit specification of the assumptions, value judgments, and technical estimates used in ranking the sites.

The comprehensive, explicit disclosure made possible by the multiattribute utility technique is both a strength and a weakness. Its strength is that it documents a difficult and controversial decision. Its weakness is that the documentation itself will be, of necessity, complex, lengthy, and burdened with concepts that are themselves formidably technical and hard to explain.

The complexity of the multiattribute utility technique demands scrupulous, methodical implementation, and it is crucial that DOE take time to do the job right. More time than is currently planned by DOE to complete the Environmental Assessments may well be needed, but the importance of the decision on site characterization to the implementation of the Nuclear Waste Policy Act as a whole strongly supports the wisdom of a careful, comprehensive application of the technique. A prompt decision now by DOE to take additional time would also permit internal and external review of the key technical components of the multiattribute utility technique.

A potential difficulty is that the siting guidelines specify a hierarchy of importance between the pre- and post-closure groups of factors and among the three groups of pre-closure factors. While the general intent of specifying an order of priority is clear, there remains the possibility that translating a vaguely worded requirement into precise mathematical constraints on the numerical weights estimated as part of the multiattribute utility technique (as proposed by DOE) may lead to implicit value judgments that DOE is not prepared to defend. An early concern of the analysis should be to determine whether or not this is in fact the case.

The Board recommends that the methodology and assessment portion of Chapter 7, because of its importance in site ranking, be written so that it can stand alone with an introduction that puts the candidate site selection process in perspective. The Board also urges that the theory, data, and methods used in the site recommendation process be presented clearly and understandably so that all uncertainties and judgments are made explicit. The Board recognizes that a major advantage of the multiattribute utility technique approach is that it can facilitate such a presentation.

The Board appreciates the difficulty faced by DOE in responding to all the comments on the Draft Environmental Assessments, in revising the assessments, and in applying a more refined technique to help select the three candidate sites. We compliment DOE on the way in which they have responded with a revised methodology to our concerns and those of others about the Draft

Environmental Assessments. The Board supports the rigorous application of the new methodology and would be pleased to amplify any of the points raised in this letter or in our meeting of October 1-3, 1985 with the staff of the Office of Civilian Radioactive Waste Management.

Sincerely,

Frank L. Parker

Frank L. Parker
Chairman
Board on Radioactive
Waste Management

FLP/jc

Department of Energy
Washington, DC 20585

OCT 2 1 1985

Dr. Frank L. Parker
Chairman
Board on Radioactive
Waste Management
National Academy of Sciences
2101 Constitution Ave., N.W.
Washington, D.C. 20418

Dear Dr. Parker:

I have received the Board's letter report on the methodology we will apply to aid our decision of sites to be selected for site characterization for the first geologic repository. I would like to thank you and the members of the Board for your thoughtful and concise review. We are pleased that the Board has concluded that the methodology, if properly applied, is an appropriate decision-aiding tool. We will give careful consideration to the Board's recommendations and suggestions.

I would appreciate it if you would express my personal thanks to all the Board members for their commitment, and yours, in undertaking this assignment with the priority that this important task deserves. I would also like to express my appreciation to Peter Myers and the Academy Reports Review for their excellent support in allowing us to receive your report so quickly.

Sincerely,

Ben C. Rusche

Ben C. Rusche, Director
Office of Civilian Radioactive
Waste Management

cc: Dr. Peter Myers
Staff Director
Board on Radioactive Waste Management
National Academy of Sciences

Department of Energy
Washington, DC 20585

OCT 30 1985

Dr. Frank Press
President
National Academy of Sciences
2101 Constitution Ave., NW
Washington, DC 20418

Dear Dr. Press:

As you are aware the Department of Energy has the principal responsibility for implementing the Nuclear Waste Policy Act to site, construct, operate and decommission the nation's first repository for the permanent disposal of high-level radioactive waste. In carrying out the program, the Academy's Board on Radioactive Waste Management has provided valuable analytical reviews of key program activities.

In particular, we recently received the letter report from the Board, in response to our request that they undertake a review of the methodology we proposed for aiding the selection of sites to be characterized. We were pleased that the Board concluded that the multiattribute utility technique which we proposed is an appropriate tool if implemented correctly. We are also grateful for the unusually prompt response which, I believe, reflects both the importance of the program and the dedication of the Board and the Academy.

The report of the Board also described several recommendations for DOE to consider in applying the methodology. One of the Board's recommendations is that an independent panel of outside experts conduct a comprehensive review of the analysis. We agree. In reviewing this recommendation, we believe the Board is the best qualified group to undertake this review in a timely manner. Therefore, I ask that you approve the Board undertaking this independent review of our application of the methodology, to provide an additional assurance that we have applied the methodology in an appropriate and reasonable way. We have agreed with the Board in past conversations that it is not appropriate to ask the Board to validate, agree with, or defend the technical data that serve as inputs to the methodology.

If you approve this task, we will work with your staff, to develop a mutually convenient schedule for the Board's further involvement. We look forward to your reply.

Sincerely,

Ben C. Rusche, Director
Office of Civilian Radioactive
Waste Management

cc: Peter Myers, Staff Director
Board on Radioactive Waste Management
National Academy of Sciences

Dr. Frank Parker, Chairman
Board on Radioactive Waste Management
National Academy of Sciences

Department of Energy
Washington, DC 20585

NOV 6 1985

Dr. Peter B. Myers
Staff Director
Board on Radioactive Waste Management
National Academy of Sciences
2101 Constitution Avenue, N.W.
Washington, D.C. 20418

Dear Dr. Myers:

We are pleased that the Board on Radioactive Waste Management (BRWM) has agreed to assist us further in the development of a sound decision-aiding methodology to aid the selection of sites for site characterization. The purpose of this letter is to confirm our understanding of the process and schedule for your further involvement.

As we have discussed, two three-day meetings appear necessary, the first December 12-14, 1985, and the second on January 14-16, 1986. The purpose of the first meeting will be to discuss and receive BRWM's comments on DOE's preliminary influence diagrams and performance-measure scales. To enable the BRWM to prepare for this meeting, we will deliver to you, before December 5, complete (i.e., postclosure and preclosure) sets of preliminary influence diagrams and performance measures.

Having finalized these two critical pieces of the methodology, we will then proceed with the remaining steps of the methodology including the development of utility curves and weighting factors.

We anticipate that this work will require nearly all of the short time between Christmas and the January meeting. Accordingly, we do not expect to be able to provide the BRWM with extensive review material much before the January meeting. We propose to spend the time at the January meeting reviewing in detail the basis for our utility curves and weighting factors. Because of the judgmental nature of the utility curves and weights, we do not expect the BRWM to recommend the use of specific curves. Instead, we will ask that the BRWM attest to the <u>reasonableness</u> of our value judgments.

Please contact Tom Isaacs of my staff on (202) 252-9692 if you have any questions.

Sincerely,

original signed by Ben C. Rusche

Ben C. Rusche, Director
Office of Civilian Radioactive
Waste Management

cc: Dr. Frank Press, President
National Academy of Sciences

Dr. Frank Parker, Chairman
Board on Radioactive Waste Management
National Academy of Sciences

Department of Energy
Washington, DC 20585

MAR 17 1986

Dr. Peter Myers
Staff Director
Board on Radioactive Waste Management
National Academy of Sciences
2101 Constitution Avenue, N.W.
Washington, D.C. 20418

Dear Dr. Myers:

Pursuant to discussions we have had with you and Dr. Press, we are pleased to submit for review and comment by the Board on Radioactive Waste Management most of what will be finalized into the Candidate Site Recommendation Report. The application of the decision-aiding methodology described therein will provide a technical basis, in conjunction with the provisions of the DOE Siting Guidelines specifying consideration of other information, for recommending three sites for site characterization. To facilitate your review of the report, we describe below its contents with reference to Attachment 1.

The report is divided into a main text consisting of 7 chapters and 8 appendices. Chapter 1 presents mostly background information on the repository program and on the siting process leading to the selection of five sites for nomination for site characterization. This chapter is provided in its entirety.

Chapter 2 presents an overview of the methodology and its relationship to the Siting Guidelines. This chapter is provided in its entirety.

Chapter 3 together with Appendices B, C, and D present the postclosure analysis of the sites. As agreed at last December's meeting, these materials are also provided in their entirety. Because of the sensitivity of these materials -- the actual site ratings are included -- we ask that their content remain confidential.

Chapter 4 together with Appendices E and F present the preclosure analysis of sites. As agreed, only the site ratings for one site are included. In order to edit out the comparative material, Chapter 4 and Appendixes E and F will be delivered tomorrow.

Appendices A and G are also included in their entirety. Appendix A identifies the participants in the development and application of the methodology. Appendix G provides the detailed assessments used to specify the multiattribute utility function. It focuses on the preclosure utility function.

Chapters 5, 6, 7 and Appendix H are not completed at this writing. An important part of Chapter 5 is the weighting of postclosure results and preclosure results to obtain an overall ranking of sites. Because of previous BRWM comments on this topic, we will be prepared to discuss this with the BRWM at next week's meeting. If it pleases the BRWM, we will be prepared to give a short briefing (approximately 2 hours) on the application of the methodology.

We look forward to the meeting, and if we can be of further assistance until then, please do not hesitate to call.

Sincerely,

/S/

Ben C. Rusche, Director
Office of Civilian Radioactive
Waste Management

Attachment and Enclosures

NATIONAL RESEARCH COUNCIL
COMMISSION ON PHYSICAL SCIENCES, MATHEMATICS, AND RESOURCES
2101 Constitution Avenue Washington, D.C. 20418

BOARD ON
RADIOACTIVE WASTE MANAGEMENT
(202) 334-3066

OFFICE LOCATION:
JOSEPH HENRY BUILDING
21ST STREET AND
PENNSYLVANIA AVENUE, N.W.

April 10, 1986

Mr. Ben C. Rusche, Director OCRWM
U.S. Department of Energy
RW-1/Forrestal
Washington, D.C. 20585

Dear Mr. Rusche:

In response to your August 29, 1985, request that the National Research Council's Board on Radioactive Waste Management (Board) conduct "an independent review of the methodology to be used to evaluate sites for consideration as candidate sites for characterization for the first geologic repository," and your October 30, 1985, specific request that we further undertake an "independent review of [the] application of the methodology," the Board has reviewed portions of the Department of Energy's (DOE or Department) March 17, 1986, draft of the final Candidate Site Recommendation Report (CSRR). The Board has previously provided DOE with comments on the Department's original draft methodology by its letter of April 26, 1985, and comments on a revised methodological approach by its letter of October 10, 1985.

It is neither appropriate nor the intent of the Board to address the ultimate ranking or the recommendation of specific sites, both of which go beyond the implementation of the decision-aiding methodology. Accordingly, the chapters and appendices reviewed by the Board and its consultants were limited to an overview of the decision-aiding methodology, its application to post-closure factors for all five candidate sites, and its application to pre-closure factors at one site. The Board chose not to review, and at its own request did not have access to, DOE's rankings on pre-closure factors, rankings combining post-closure and pre-closure factors using the decision-aiding methodology, or the final recommendation of sites for characterization. Because of the limits on available time and the volume of the documentation involved, the Board did not attempt to review the site-specific data in the draft Environmental Assessments (EAs). To help conduct this review, the Board enlisted the aid of four consultants, three of whom are recognized experts in multi-attribute utility analysis and its applications.

I. THE DECISION-AIDING METHODOLOGY

The Board commends DOE for the high quality of the chapters that were reviewed. The use of the multi-attribute utility method is appropriate, and the Board is impressed by the care and attention to detail with which it has been implemented. It should be noted, however, that the Board's focus was on methodology and its implementation and that the Board has not reviewed in detail the data and judgments on which the conclusions from the multi-attribute procedure are based.

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 multi-attribute utility method used by DOE is a satisfactory and appropriate decision-aiding tool. The multi-attribute 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.

The Board is disappointed that DOE did not follow the recommendation, made in the Board's April 26 and October 10 letters, that independent experts be brought into the assessment process itself as well as into the review of the process. As noted in the October letter, "The Board is concerned that DOE's use of its own technical experts to assess performance by this subjective method may mask the degree of real uncertainty associated with post-closure issues." The Board has seen nothing to indicate bias in the implementation of the method and recognizes that, in this instance, the DOE sensitivity analysis applied to post-closure issues indicates that the rankings on these issues would not change with reasonable or plausible changes in the parameters and judgments. In other applications of the methodology, however, the results may not be so insensitive to the judgments. In that event the addition of independent experts in the generation of those judgments would be important. A final concern with the review draft remains: the need for additional documentation beyond that included in the March 17, 1986, draft of the reasoning and judgement involved in the choices of the scores and probabilities associated with the various scenarios. On the basis of discussions with DOE staff, the Board anticipates a satisfactory response to this concern in the final version of the CSRR.

II. POST-CLOSURE ANALYSES

The DOE application of the multi-attribute utility method for the post-closure factors provides useful information concerning the Department's current judgment of the expected performance of the sites for the post-closure period and on its judgment of the range of uncertainties. The Board reiterates that, when adequate data and validated models are available, conducting a probabilistic "performance assessment" using quantitative models, as recommended by the National Research Council[1], is a scientifically defensible method of integrating and weighting the post-closure factors at each site. In the absence of performance assessments capable of comparing the expected post-closure performance of the sites directly, judgments of experts are appropriately used to develop subjective estimates of the post-closure factors at each site. DOE has implemented this approach using its technical experts and those of its contractors, and it appears to have incorporated information resulting from models on the release and migration of radionuclides to the "accessible environment" (as defined by the Environmental Protection Agency (EPA)). The Department has also conducted an extensive sensitivity analysis.

The DOE analysis assesses post-closure performance based on probabilities of releases to an arbitrarily defined and universally applied accessible environment. This approach is consistent with the DOE siting guidelines and follows the requirements for repository performance established in the EPA Standard (40 CFR 191). Because this approach does not take into account the differences among sites in pathways from the EPA accessible environment to the biosphere, and thus the potential consequences of any given release at the accessible environment, the Board recommends that the DOE decision makers consider such differences in addition to the results of the decision-aiding methodology. Chapter 6, which the Board has been told considers decision factors beyond the scope of the multi-attribute utility method, would seem to be the appropriate place to incorporate such consideration for the present decision. If the multi-attribute utility method is applied to a future site selection process, however, the evaluation of relative environmental consequences should become part of the post-closure analysis. Such an approach would facilitate comparison of post- and pre-closure results.

III. PRE-CLOSURE ANALYSES

The pre-closure results are stated in terms of dollar costs, estimated lives lost in building and operating a repository, and performance measures covering esthetic, archeological, biological and socioeconomic impacts. Although the multi-attribute utility method significantly clarifies the

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[1] National Research Council 1983. A Study of the Isolation System for Geologic Disposal of Radioactive Wastes. Board on Radioactive Waste Management, Panel on Waste Isolation Systems. National Academy Press, Washington, D.C.

relative importance of the many factors considered in ranking sites, the reduction of all attributes to a single quantitative scale depends, in this application, upon the value tradeoffs made by DOE staff. In addition to the sensitivity analysis they conducted, the Department decision makers might have found it beneficial in the selection of objectives and in weighing pre-closure factors to draw on value judgments from a variety of sources outside the DOE.

On the basis of the Board's review of the application to a single site, it appears that the expected total repository and transportation costs will have a major, if not controlling, effect on the rankings under pre-closure factors. This recognition of the heavy dependence on cost reinforces the Board's judgment that the principal usefulness of the multi-attribute utility method is to illuminate the factors involved in a decision, rather than to make the decision itself.

IV. CONCLUSIONS

In addition to the multi-attribute decision analysis, there are other factors that must be taken into account in the final decision to select three sites for characterization. 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.

When the Board commented on the Draft Environmental Assessments a year ago, it expressed strong reservations about the methods used by DOE to select sites for characterization. The Department has made substantial progress since then. As stated in the Board's October 10, 1985, report, "...our concern about the appropriateness of the methodology, as expressed in our April 26, 1985, critique of Chapter 7 of the December, 1984, Draft Environmental Assessments, has now been addressed." DOE has now selected a decision-aiding method that the Board believes is appropriate to the complexity and technical uncertainties of the decision the Department faces in choosing sites to characterize.

Although the Board has not seen the final version of the CSRR, those parts of the draft it has reviewed include substantial documentation of the site-ranking method and the way it has been implemented. On the basis of discussions with DOE staff, we anticipate satisfactory responses to our remaining concerns about documentation in the final CSRR.

In its review of the implementation of the site-ranking methodology, then, the Board finds much to praise. It is important to note that the Board reviewed neither the data in the draft EAs nor the application of the procedures in which sites were scored and value tradeoffs were assessed. Moreover, DOE did not take the Board's advice, offered twice in writing, to involve outside groups of experts in the site-ranking process beyond this review of the implementation of the methodology by the Board. The Board has seen nothing to indicate bias in the Department's implementation of the methodology and recognizes the value of the DOE sensitivity analysis, but the lack of external input in technical and value judgments could raise concerns about bias.

Despite the limitations in the scope of the Board's review, we believe the methods used in the CSRR provide a sound analytical basis for aiding the site characterization decision. The Board commends the Department of Energy for taking the time and devoting the resources to identify and apply a comprehensive decision-aiding methodology. We believe that the methodology the Department has selected represents "state of the art" and is adequate and appropriate for this purpose. We compliment DOE on its care and diligence in implementing the site-ranking methodology, and encourage the Department to build on the experience it has gained as it continues the search for a geologic repository.

Sincerely,

Frank L. Parker

Frank L. Parker
Chairman, Board on
Radioactive Waste Management

FLP:jc

COMMISSION ON PHYSICAL SCIENCES, MATHEMATICS AND RESOURCES

BOARD ON RADIOACTIVE WASTE MANAGEMENT

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