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^{-9} 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.

Scenario 3: Repository-induced dissolution of the host rock

Because this scenario applies only to relatively soluble rocks, it is not considered credible at the Hanford site.

Scenario 4: Advance of a dissolution front

Because this scenario applies only to relatively soluble rocks, it is not considered credible at the Hanford site.

Scenario 5: Movement on a large fault inside the controlled area but outside the repository

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 2×10^{-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.

Scenario 6: Movement on a large fault within the repository

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.

Scenario 7: Movement on a small fault inside the controlled area but outside the repository

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 2.9×10^{-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 4.7×10^{-8} to 3.3×10^{-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 5×10^{-8}, with a range of 5×10^{-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

<u>Performance Objective and Performance Measures</u>

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 fods 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.

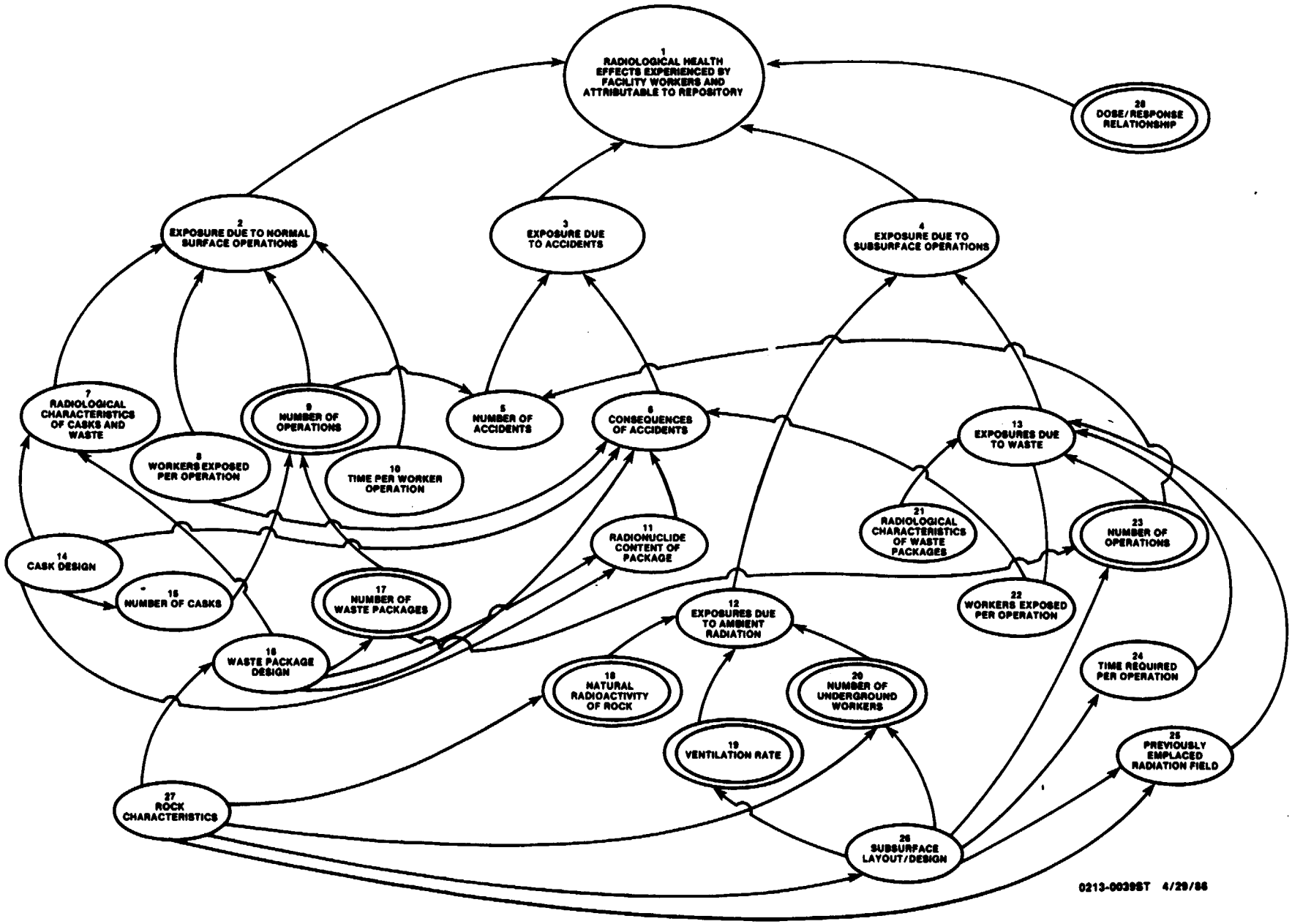

Figure E-1. Factors that influence the radiological health effects incurred by repository workers.

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.

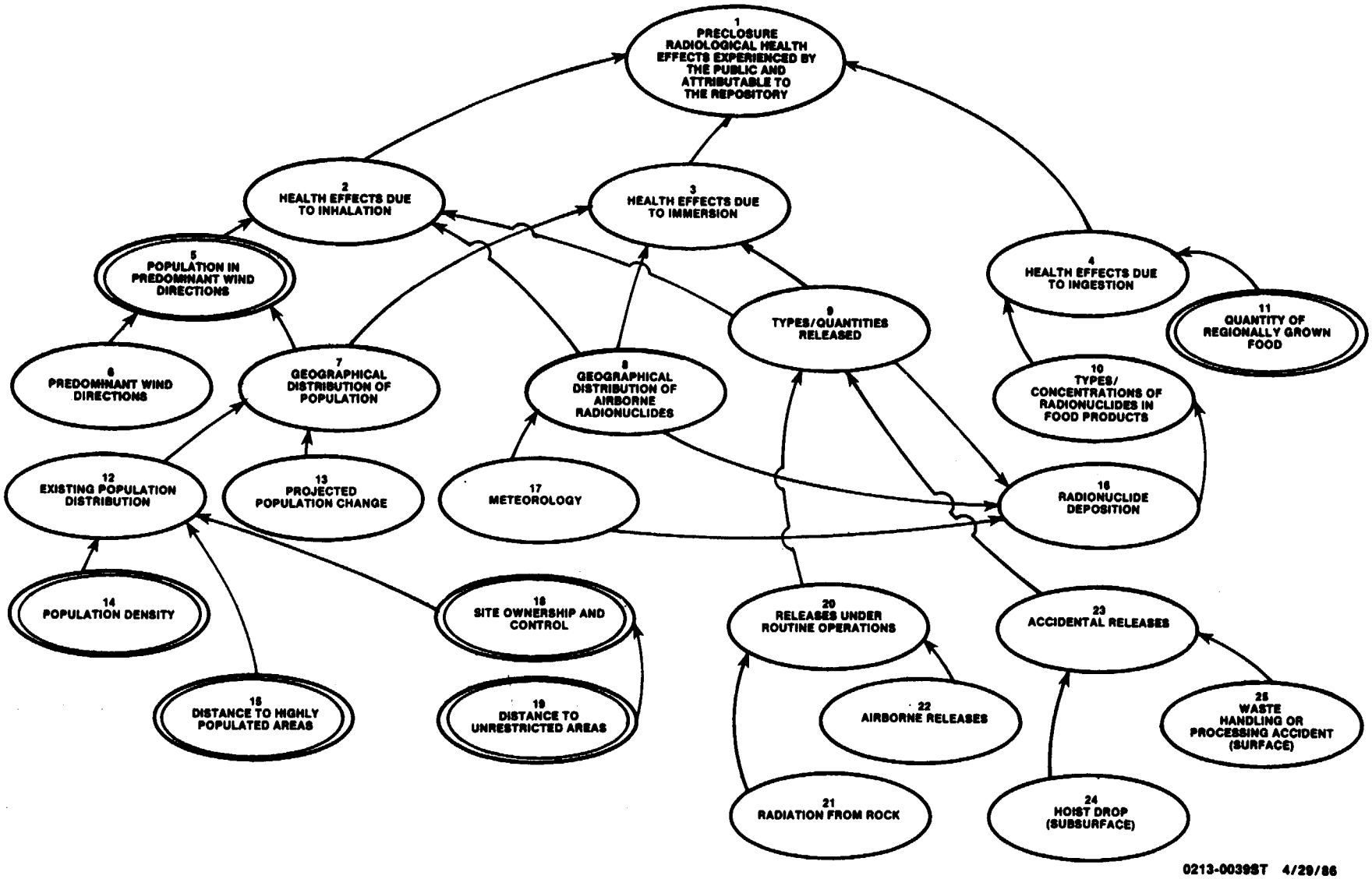

Figure E-2. Factors that influence the radiological health effects incurred by the public from the repository.

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

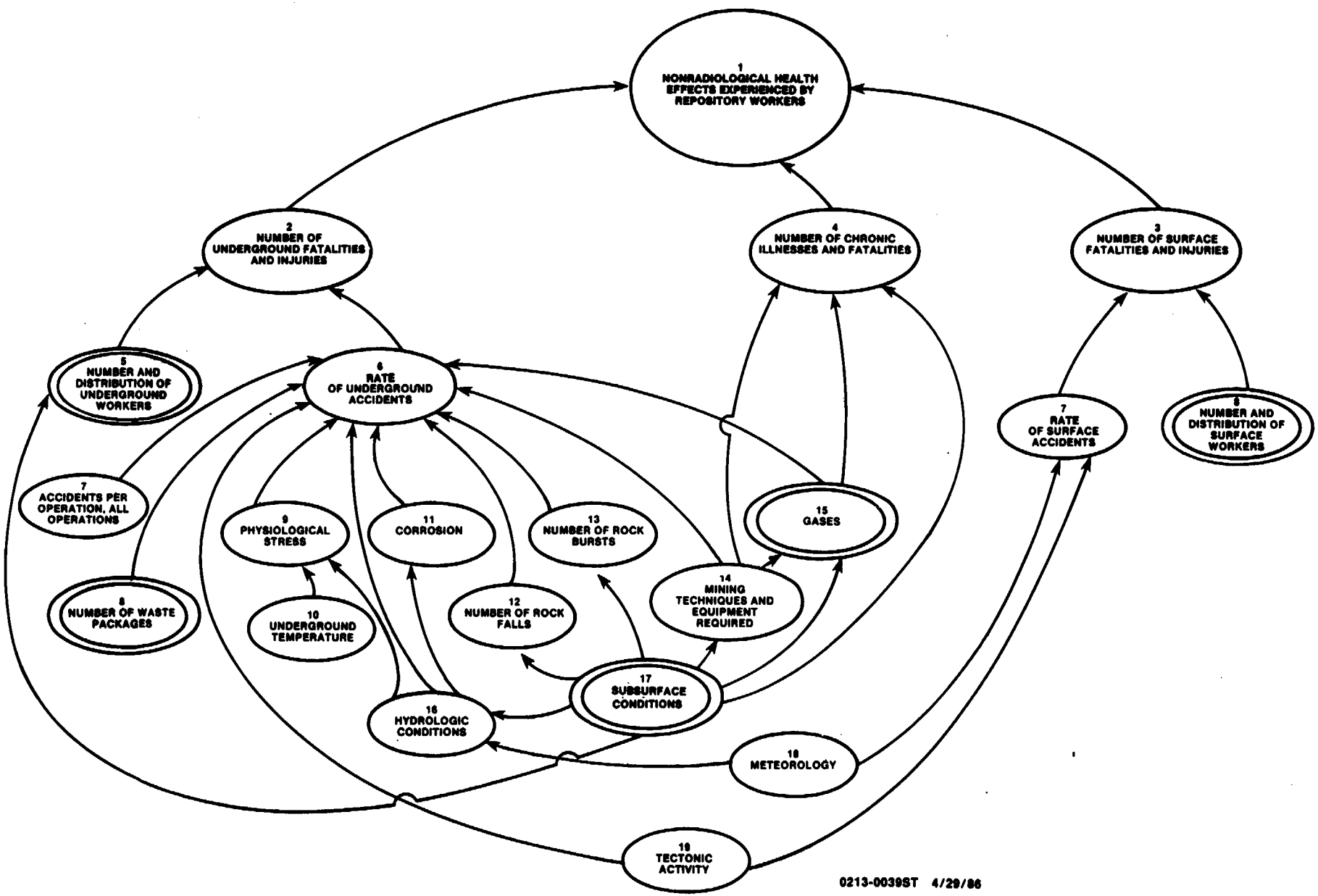

Figure E-3. Factors that influence the nonradiological health effects incurred by repository workers.

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).

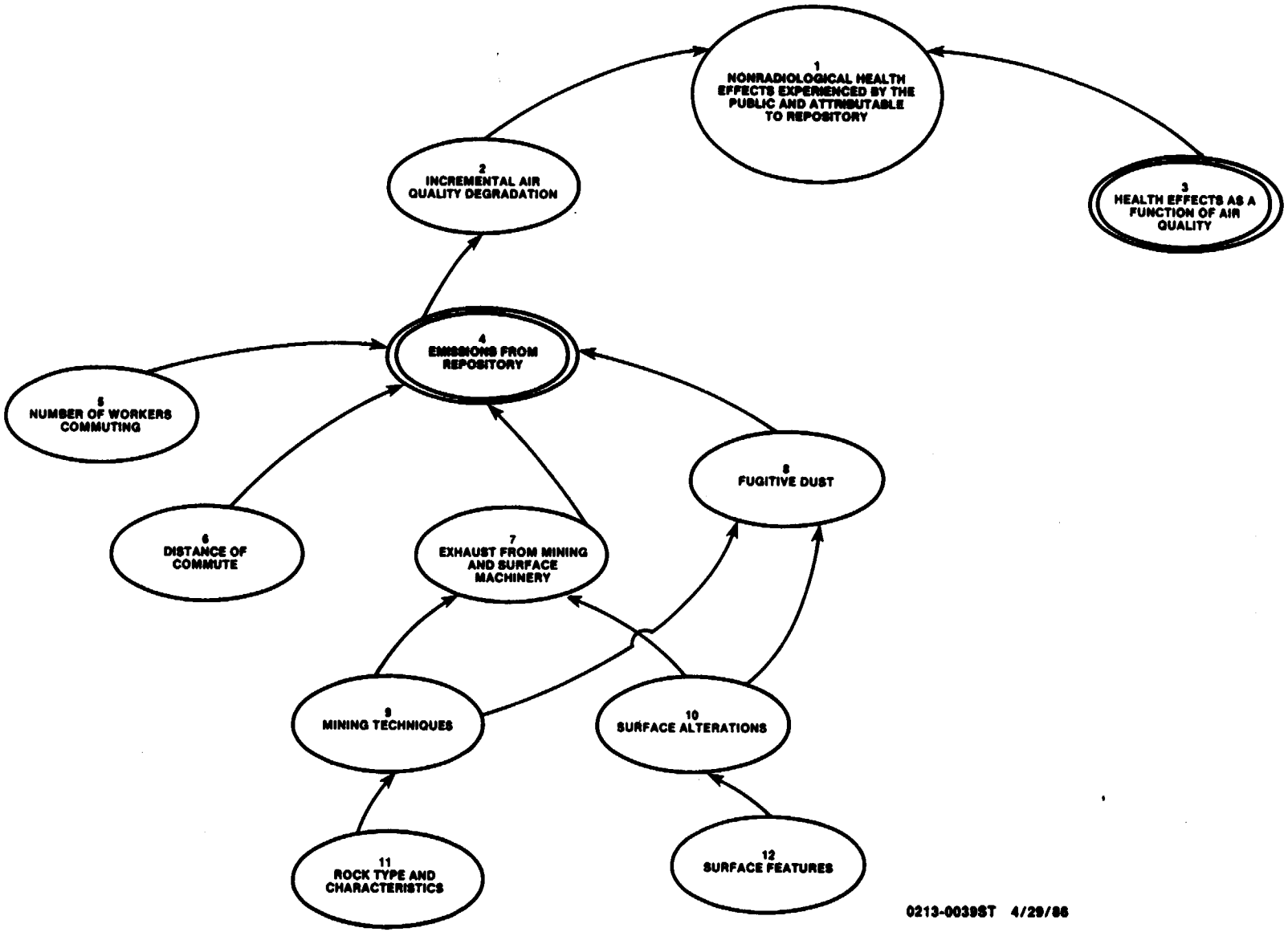

Figure E-4. Factors that influence the nonradiological health effects incurred by the public.

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).

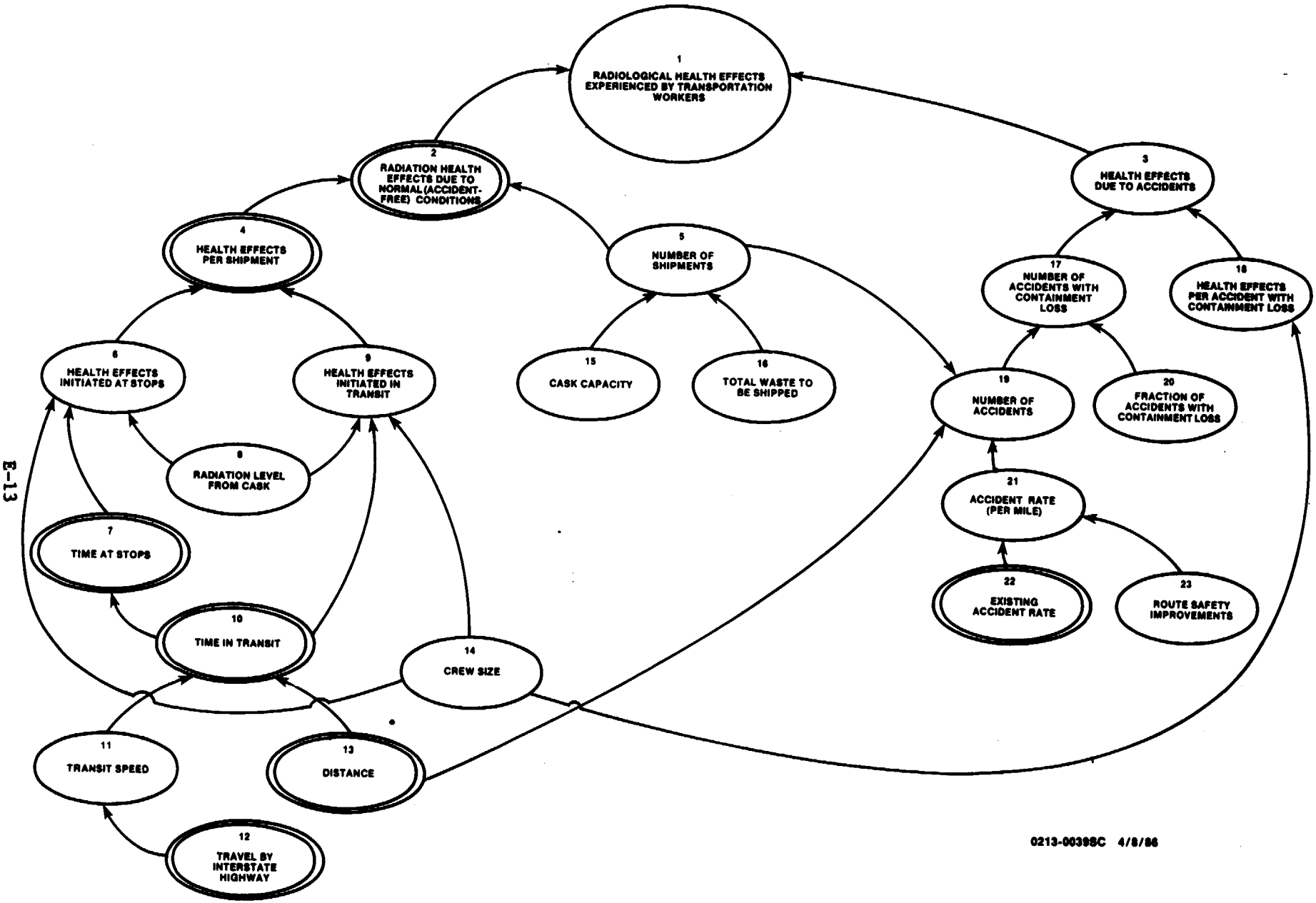

Figure E-5. Factors that influence the radiological health effects incurred by transportation workers.

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.

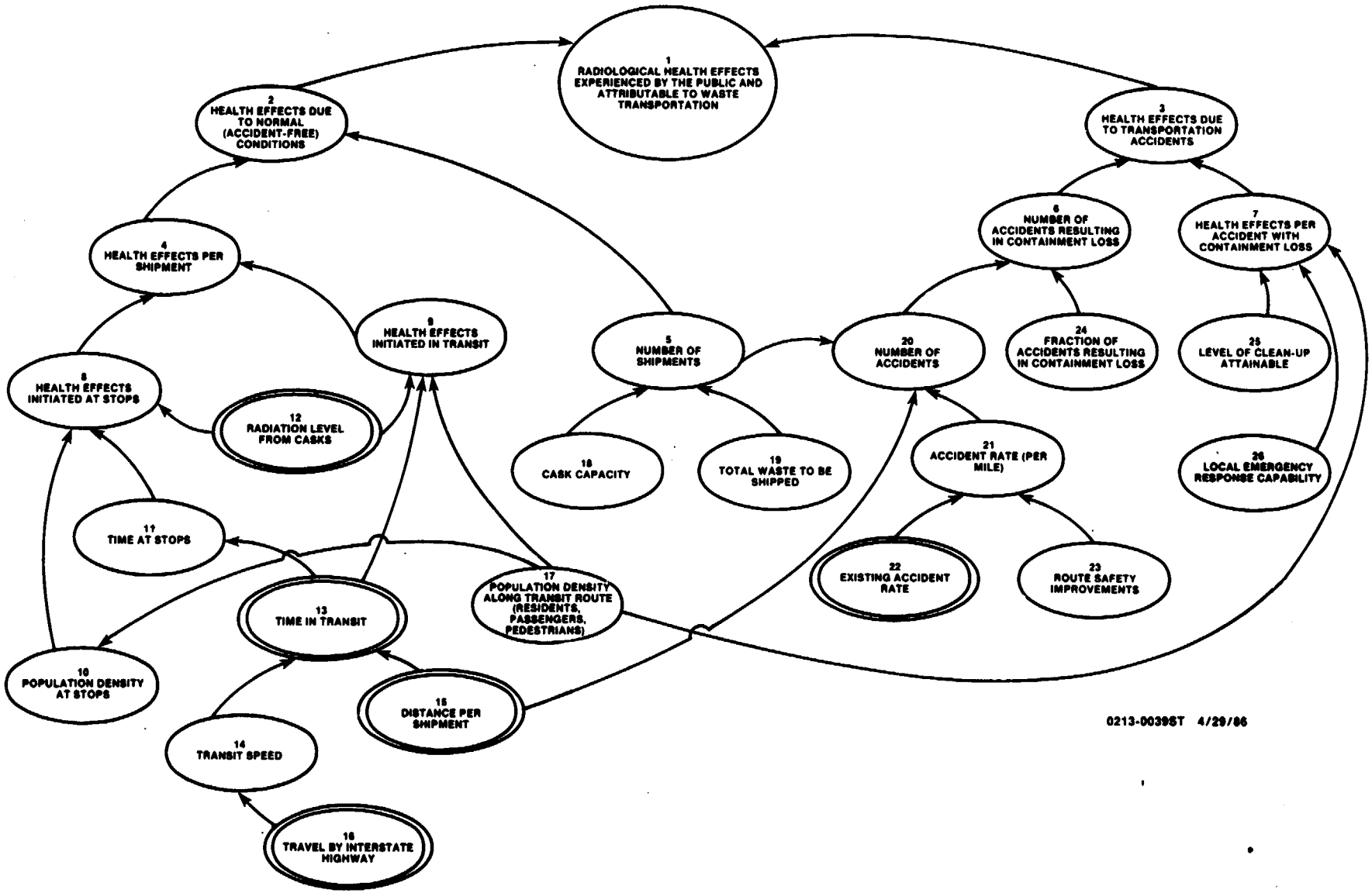

Figure E-6. Factors that influence the radiological health effects incurred by the public from waste transportation.

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.

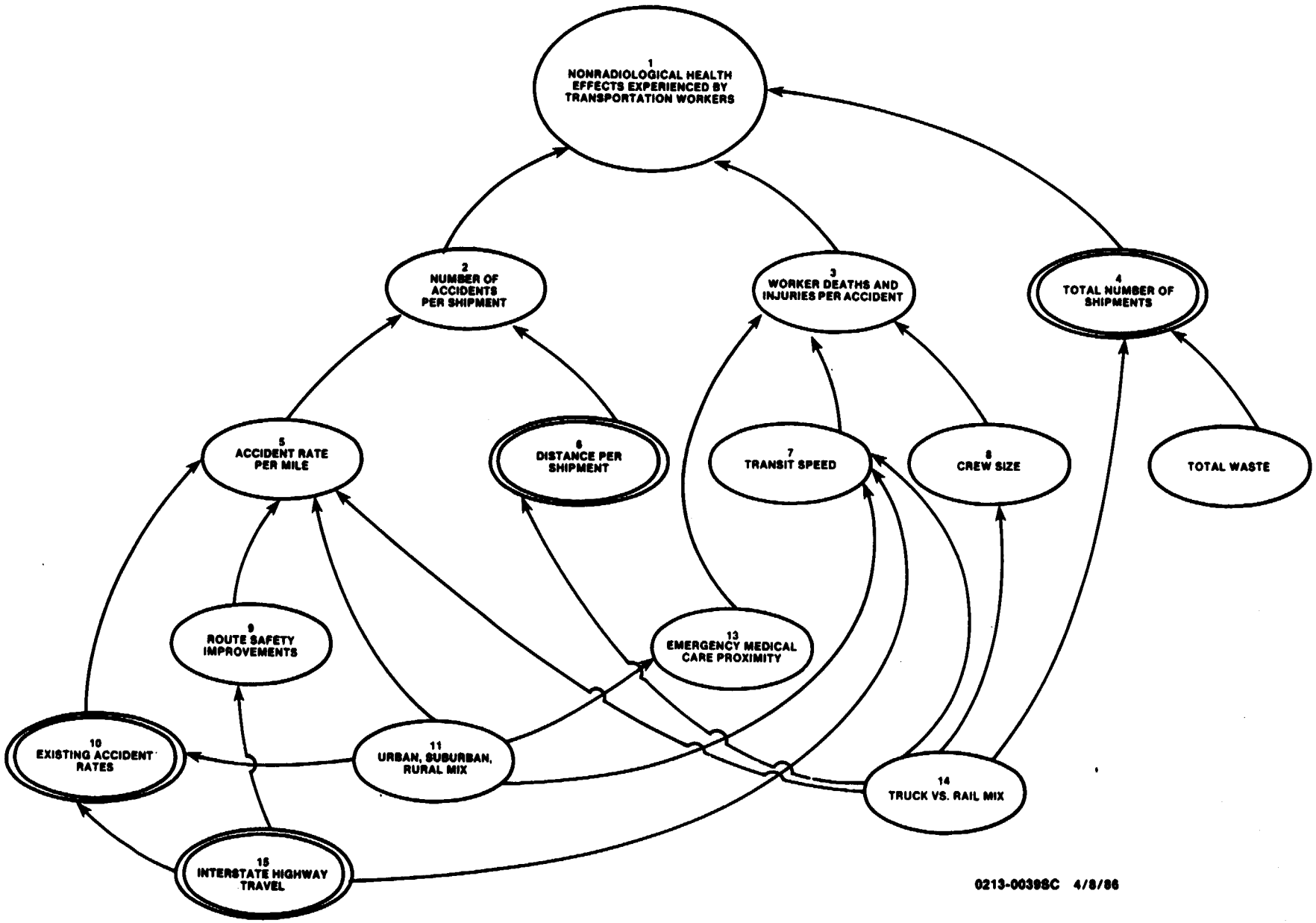

Figure E-7. Factors that influence the nonradiological health effects incurred by transportation workers.

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.

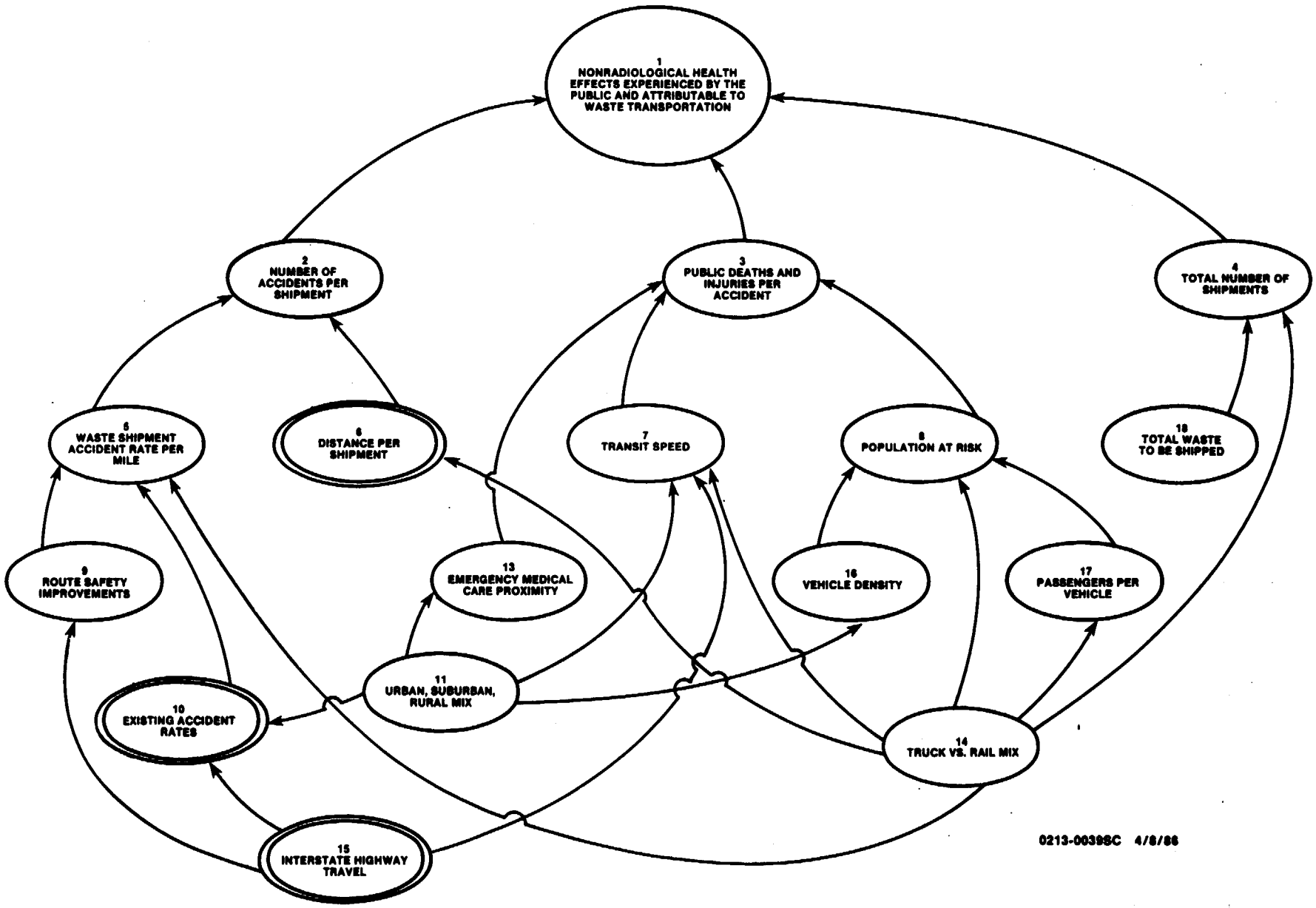

Figure E-8. Factors that influence the nonradiological health effects incurred by the public from waste transportation.

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).

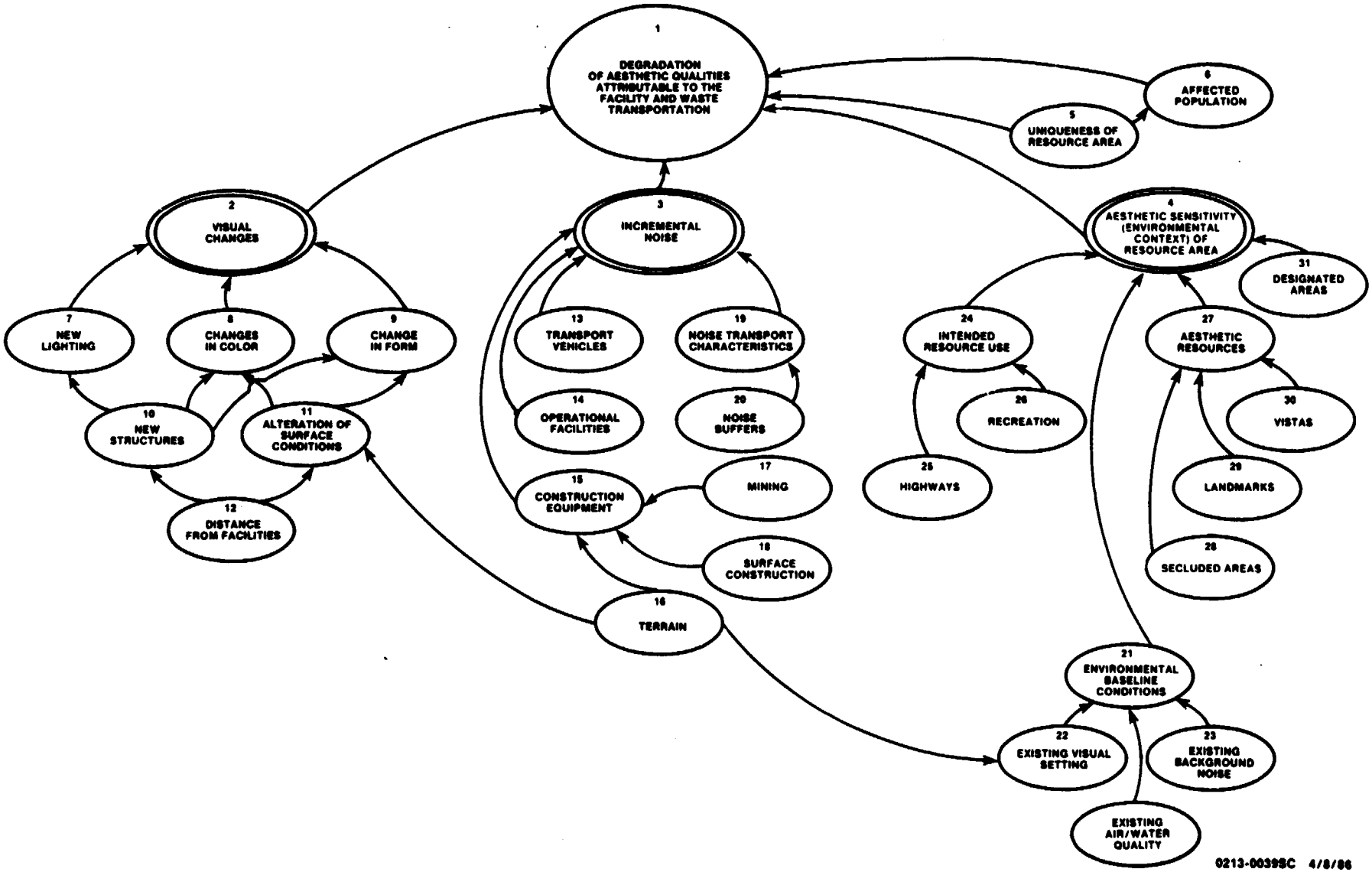

Figure E-9. Factors that influence the degradation of aesthetic quality.

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),

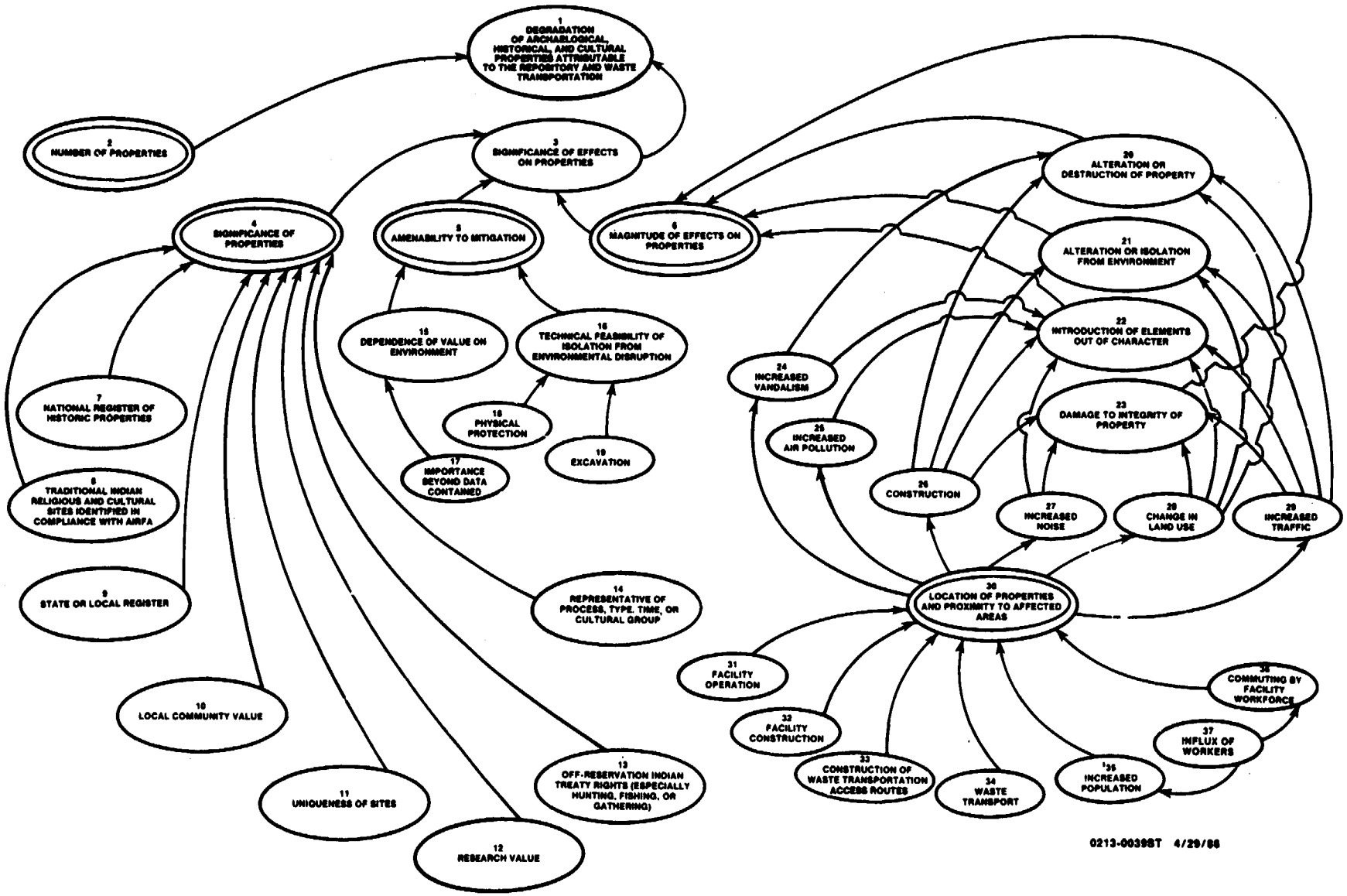

Figure E-10. Factors that influence the degradation of archaeological, historical, and cultural properties.

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.

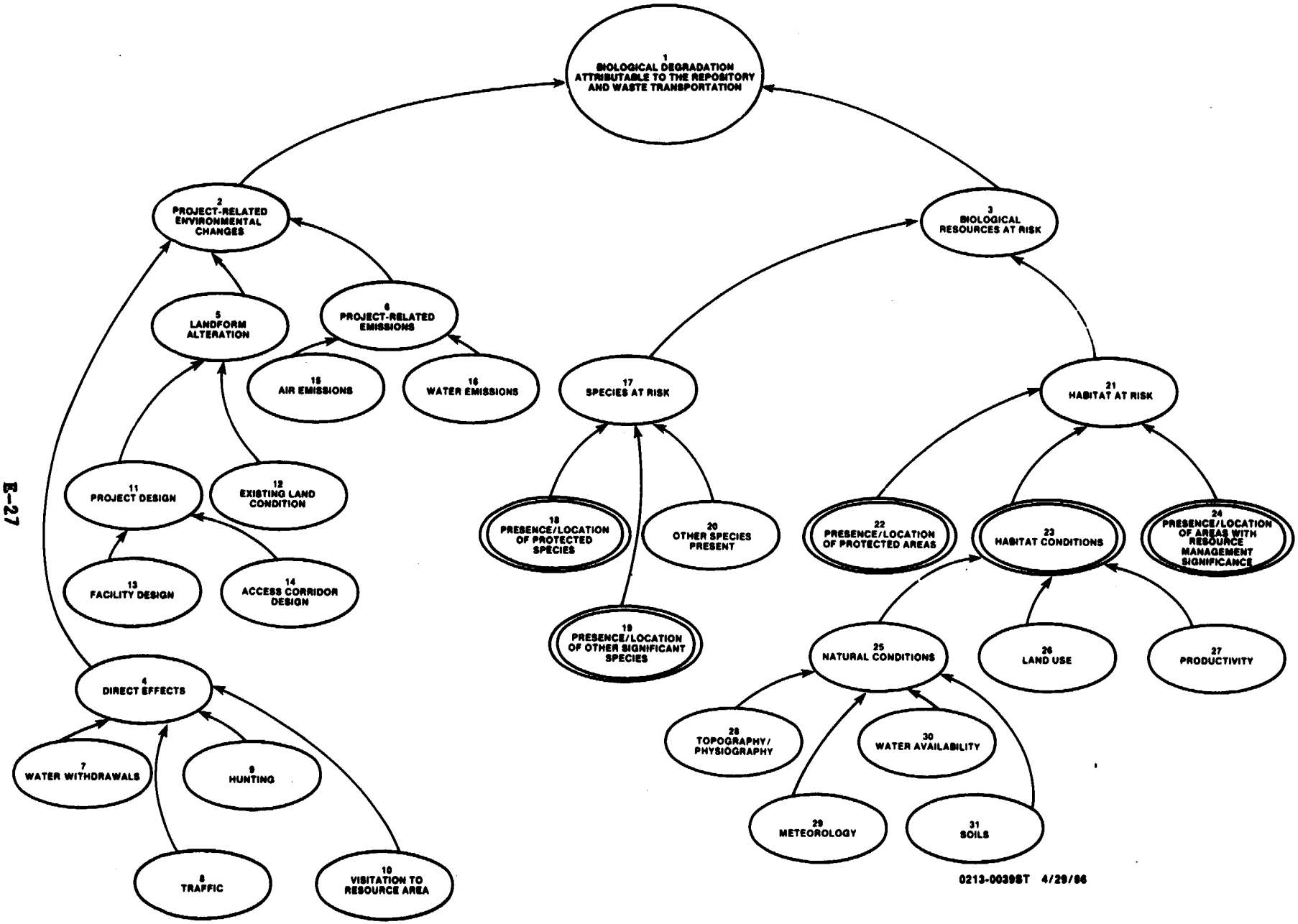

Figure E-11. Factors that influence biological degradation.

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).

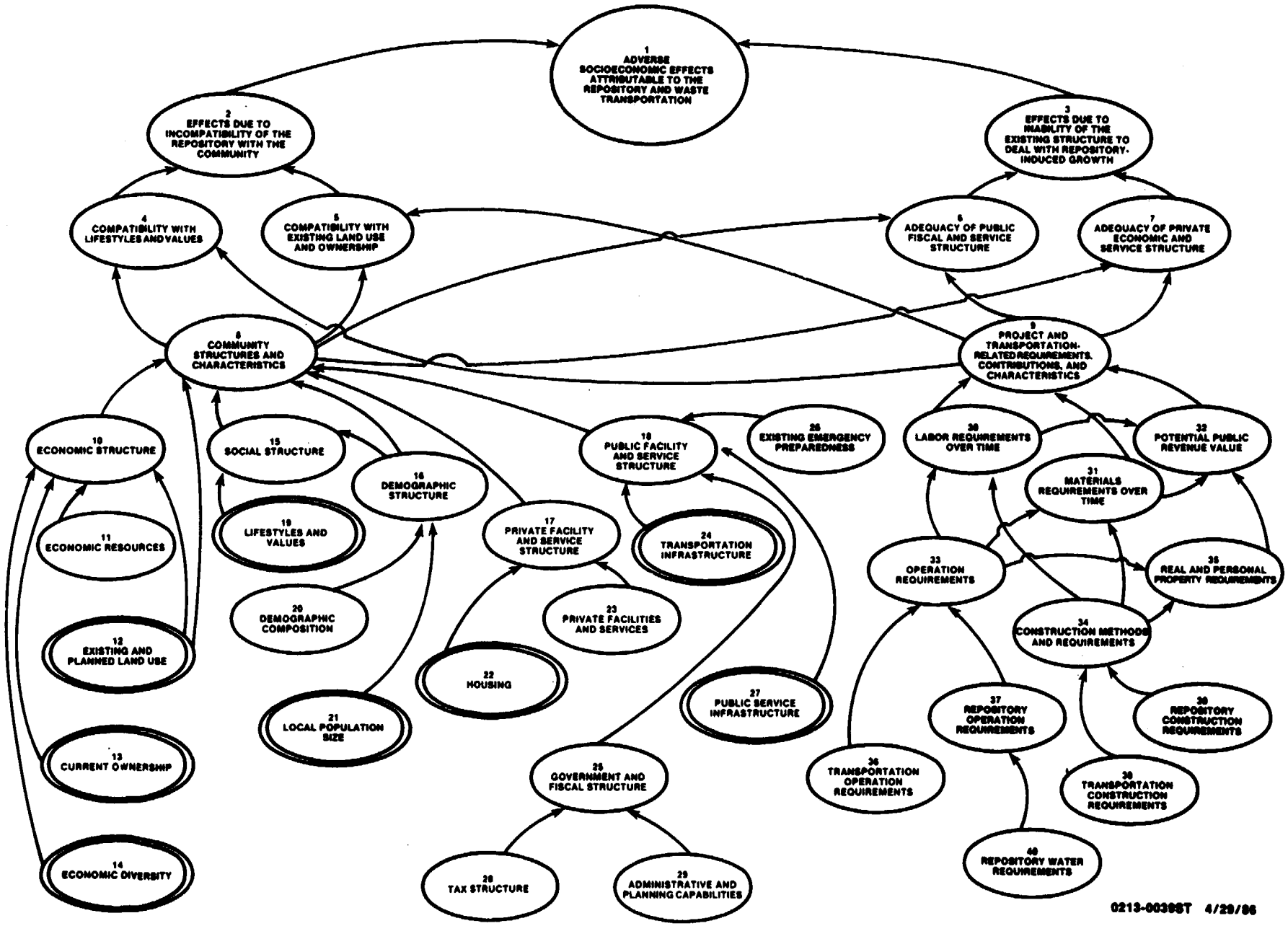

Figure E-12. Factors that influence adverse socioeconomic effects.

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.

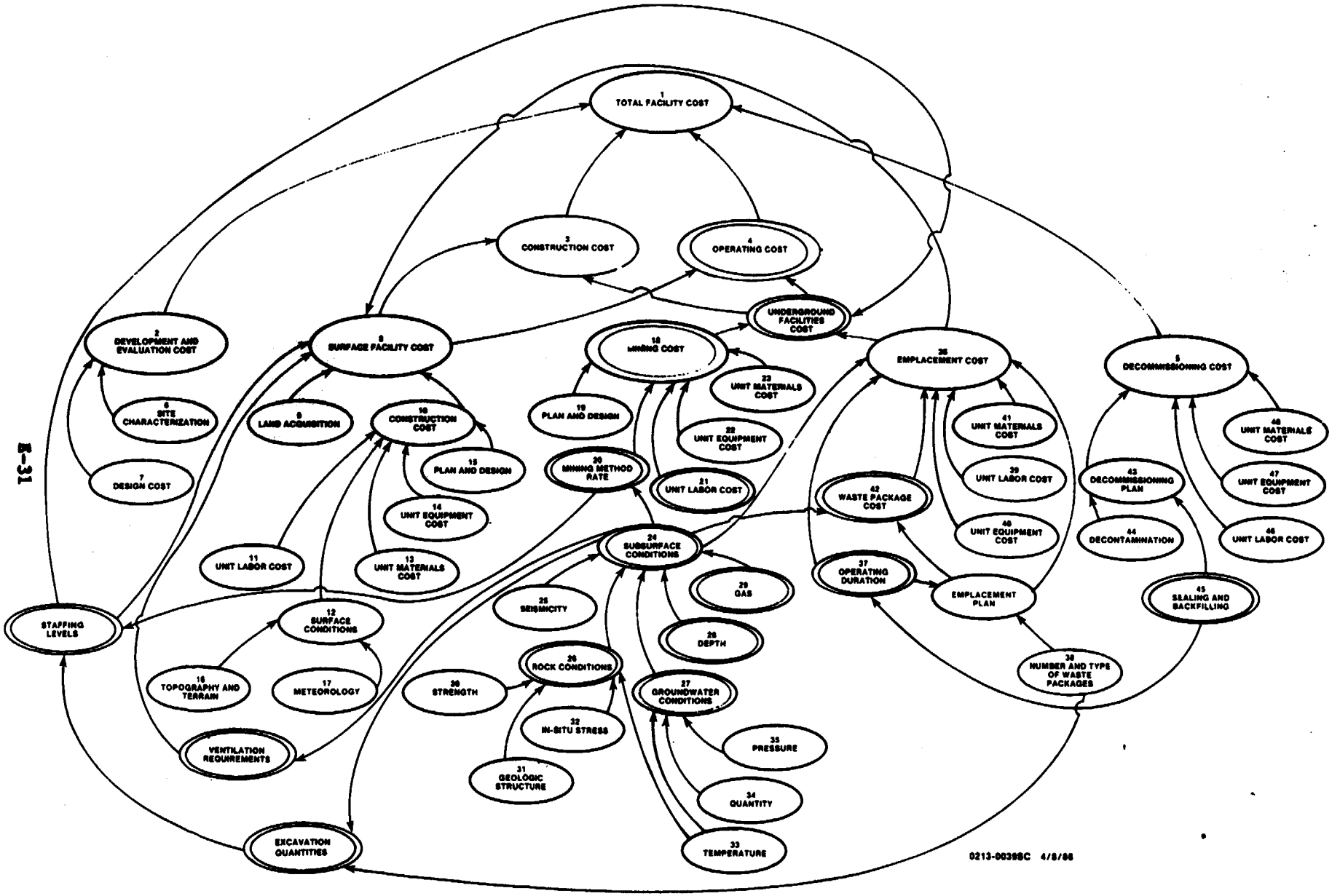

Figure E-13. Factors that influence the total cost of the repository.

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.

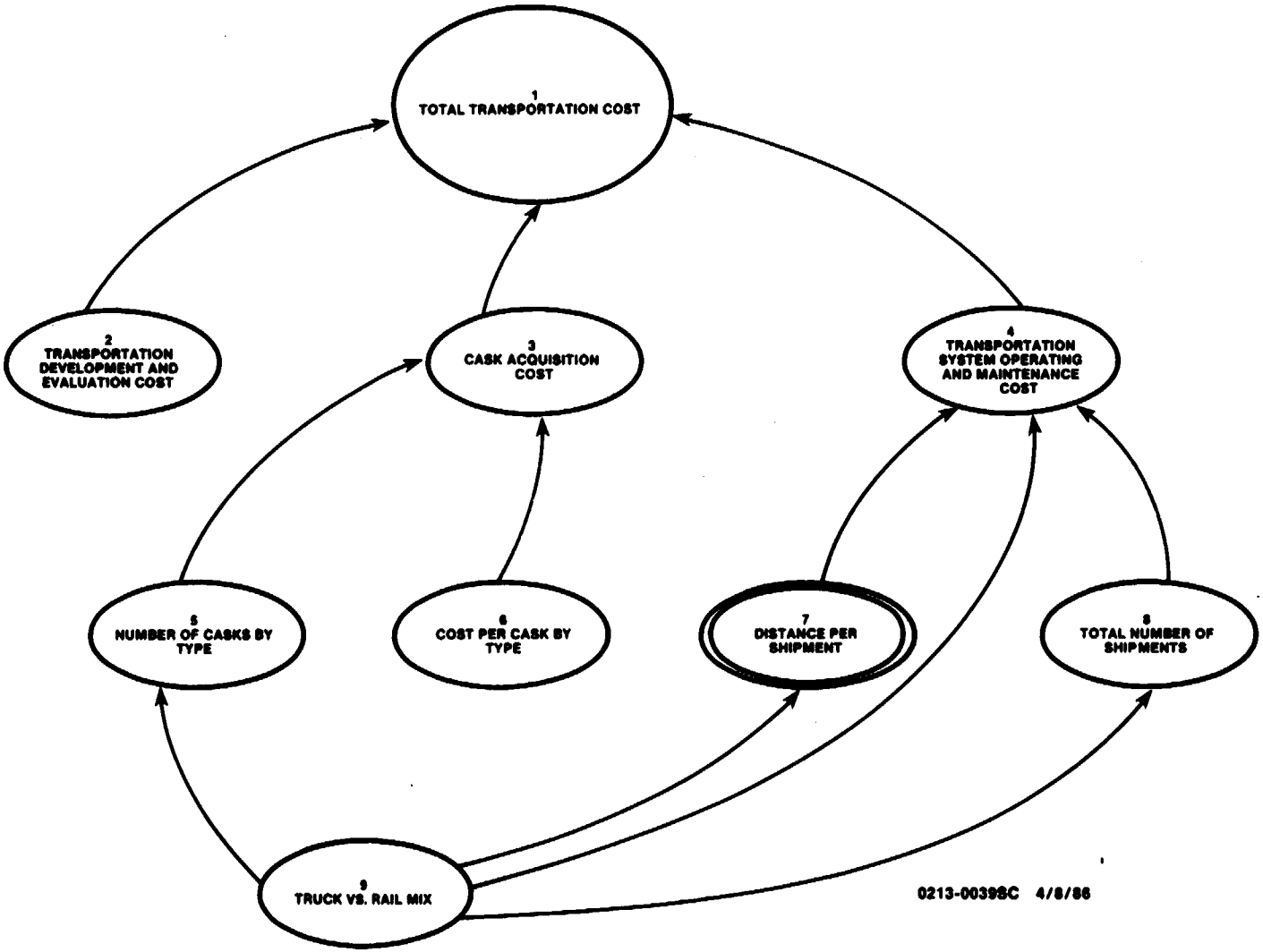

Figure E-14. Factors that influence total transportation costs.

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 in-

cluded. 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 ventila-

tion 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.)

Underground-facility construction and operation. 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 <u>all</u> 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	High-level waste[b] 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		96.4	121.4	145.1	176.8
186.7					
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		Deaf Smith		Davis Canyon		Yucca Mt.		Hanford	
	Truck	Rail	Truck	Rail	Truck	Rail	Truck	Rail	Truck	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		Deaf Smith		Davis Canyon		Yucca Mt.		Hanford	
	Truck	Rail	Truck	Rail	Truck	Rail	Truck	Rail	Truck	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
Farley 1	120	18
Farley 2	46	7
Palo Verde 1	511	72
Palo Verde 2	484	70
Palo Verde 3	448	63
Arkansas Nuclear One 1	762	108
Arkansas Nuclear One 2	187	27
Calvert Cliffs 1	893	127
Calvert Cliffs 2	853	122
Pilgrim 1	761	105
Robinson 2	581	83
Brunswick 2	799	111
Brunswick 1	791	109
Perry 1	806	110
Perry 2	747	104
Dresden 1	136	18
Dresden 2	909	126
Dresden 3	825	114
Quad-Cities 1	862	119
Quad-Cities 2	815	113
Zion 1	858	122
Zion 2	824	117
LaSalle 1	572	79
LaSalle 2	572	79
Byron 1	638	88
Byron 2	631	86
Braidwood 1	568	83
Connecticut Yankee	702	100
Indian Point 1	80	11
Indian Point 2	762	108
Big Rock Point	104	14
Palisades	796	113
Midland 2	373	49
Midland 1	334	46
La Crosse	143	19
Fermi 2	609	85
Oconee 1	759	108
Oconee 2	612	87
Oconee 3	779	111
McGuire 1	115	17
McGuire 2	73	11
Beaver Valley 1	735	104
Beaver Valley 2	272	39
Crystal River 3	676	96
Turkey Point 3	695	99
Turkey Point 4	694	99
St. Lucie 1	894	113
St. Lucie 2	486	70
Hatch 1	312	43
Hatch 2	289	40
Vogtle 1	547	78
Vogtle 2	416	60
River Bend 1	465	65
Clinton 1	528	74
Cook 1	948	135
Cook 2	933	133
Arnold	562	79
Oyster Creek	777	108
Wolf Creek	191	27
Shoreham	270	38
Waterford 3	421	61
Maine Yankee	980	140
Three Mile Island 1	723	103
Grand Gulf 1	247	35
Grand Gulf 2	340	48
Cooper	771	107
Nine Mile Point 1	700	97
Nine Mile Point 2	243	33
Millstone 1	804	111
Millstone 2	805	106
Millstone 3	36	6
Monticello	693	96
Prairie Island 1	650	92
Prairie Island 2	631	90
Fort Calhoun 1	534	76
Humboldt Bay	86	12
Diablo Canyon 2	236	34
Diablo Canyon 1	279	40
Susquehanna 1	652	90
Susquehanna 2	614	85
Peach Bottom 2	1126	156
Peach Bottom 3	1126	156
Limerick 1	679	95
Limerick 2	421	59
Trojan	330	18
Fitzpatrick	614	107
Indian Point 3	714	102
Seabrook 1	486	69
Seabrook 2	320	46
Salem 1	791	113
Salem 2	764	109
Hope Creek 1	509	71
Ginna	503	71
Rancho Seco 1	721	103
Summer	12	2
San Onofre 1	203	29
San Onofre 2	306	44
San Onofre 3	347	50
South Texas Project 1	594	82
South Texas Project 2	592	82
Browns Ferry 1	699	135
Browns Ferry 2	695	140
Browns Ferry 3	986	137
Sequoyah 1	444	46
Sequoyah 2	425	42
Watts Bar 1	518	74
Watts Bar 2	524	74
Bellefonte 1	444	64
Bellefonte 2	327	47
Hartsville A1	463	65
Hartsville A2	328	45
Yellow Creek 1	90	13
Yellow Creek 2	50	8
Comanche Peak 1	412	58
Comanche Peak 2	368	53
Davis-Besse 1	248	31
Callaway 1	360	51
Vermont Yankee	675	93
Surry 1	748	102
Surry 2	620	77
North Anna 1	365	47
North Anna 2	295	38
WNP 2	650	90
WNP 1	394	56
WNP 3	617	89
Point Beach 1	620	88
Point Beach 2	591	84
Kewaunee	634	90
Yankee	340	48
Brunswick 2	72	10
Brunswick 1	80	11
Morris BWR	150	20
Morris PWR	175	25
West Valley BWR	17	2
West Valley PWR	60	8
	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	High-level waste[b] 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 alterated 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	Site				
	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)[A]	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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Appendix G

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 ($i = 1,\ldots,16$). 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 ($i = 1,\ldots,16$). Thus, a consequence $x = (x_1,\ldots,x_{16})$ 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.

Additive independence. Attributes $X_1,\ldots,X_n$ 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.

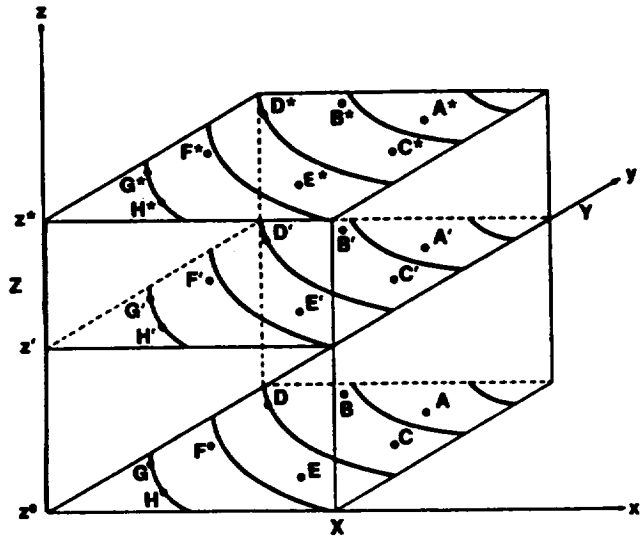

Figure G-1. Illustration of preferential independence.

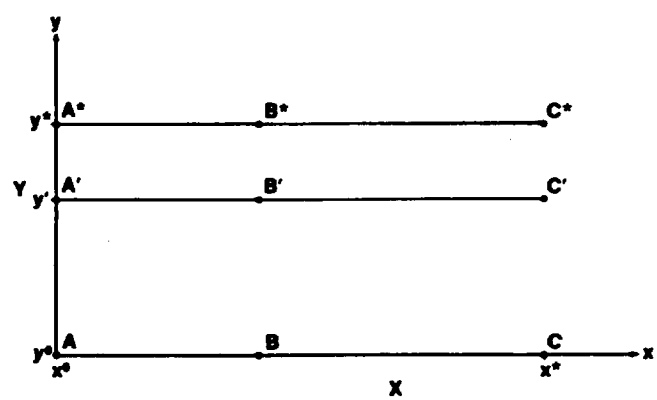

Figure G-2. Illustration of value-difference independence and utility independence.

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.

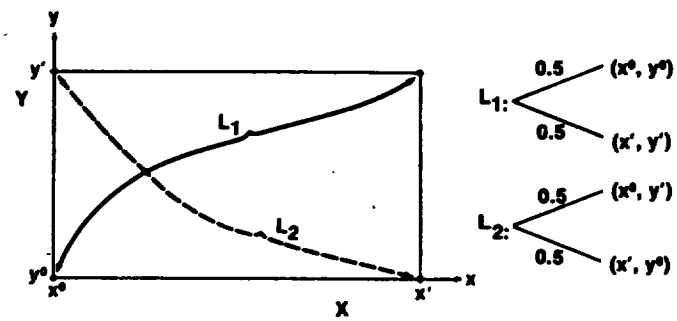

Figure G-3. Illustration of additive independence.

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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

$$\begin{aligned} u(x_1,\ldots,x_n) = & \sum_{i=1}^{n} k_i u_i(x_i) + k \sum_{i=1}^{n} \sum_{j>i} k_i k_j u_i(x_i) u_j(x_j) \\ & + k^2 \sum_{i=1}^{n} \sum_{j>i} \sum_{h>j} k_i k_j k_h u_i(x_i) u_j(x_j) u_h(x_h) \\ & + \ldots + k^{n-1} k_1 \ldots k_n u_1(x_1) \ldots u_n(x_n) \end{aligned} \qquad \text{(G-3)}$$

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_i is weak-difference independent of the other attributes replaces the condition that X_i 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

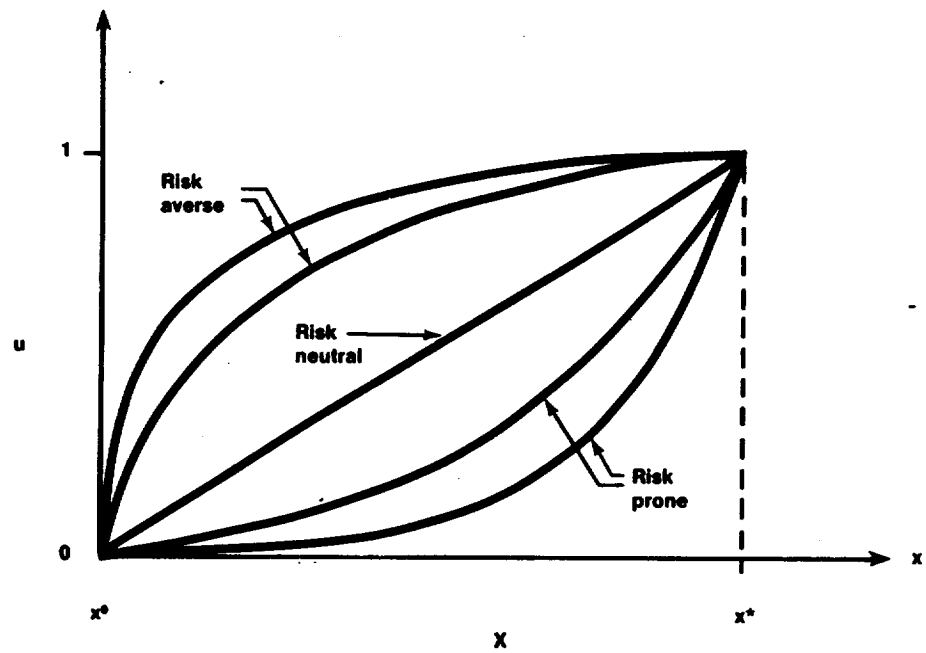
$$u(x) = a + b(-e^{-cx}), \tag{G-6a}$$

$$u(x) = a + b(cx), \tag{G-6b}$$

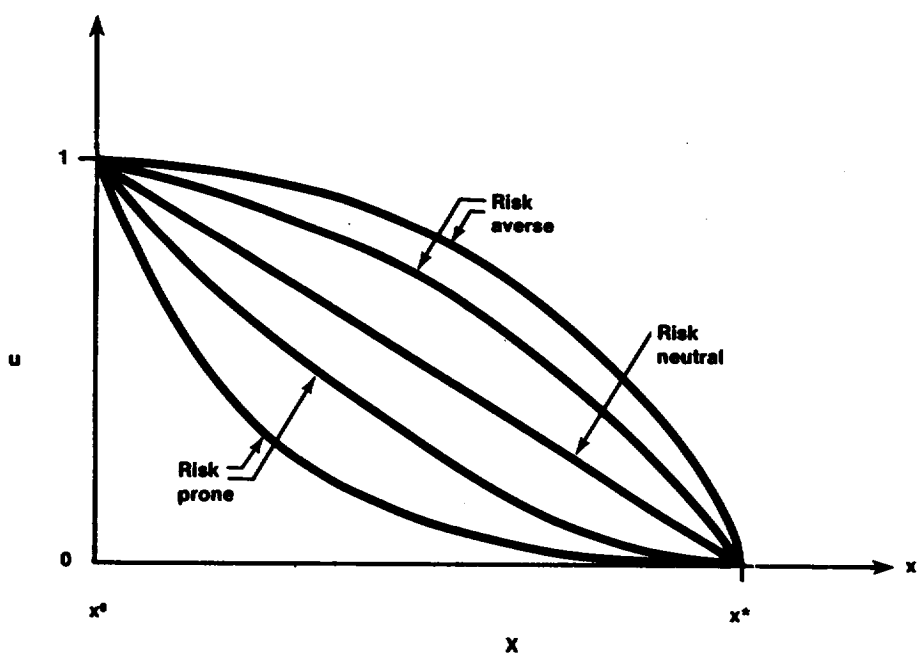
and

$$u(x) = a + b(e^{cx}), \tag{G-6c}$$

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

$$u(x) = a + b(-e^{-cx}) \qquad (b > 0,\ c > 0). \tag{G-7}$$

If u(x) is to be assessed for $x^\circ \leq x \leq x^*$, we might set

$$u(x^\circ) = 0 \qquad \text{and} \qquad u(x^*) = 1 \tag{G-8}$$

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

$$u(x^j) = p_j u(x^*) + (1 - p_j)u(x^\circ) = p_j \qquad (j = 1,\ldots,6). \tag{G-10}$$

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

$$w(x^\circ) = 0, \quad w(x^*) = 1. \tag{G-11}$$

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

$$w(x) = d + b(-e^{cx}), \tag{G-12}$$

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

$$w(x^*) - w(\hat{x}) = w(\hat{x}) - w(w^\circ). \tag{G-13}$$

Combining this with Equation G-11 yields

$$w(\hat{x}) = 0.5, \tag{G-14}$$

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 Assessing the scaling constants

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,

$$u(x_1,\ldots,x_n) = f[u_1(x_1),\ldots,u_n(x_n),k_1,\ldots,k_r], \tag{G-15}$$

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)

- 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 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

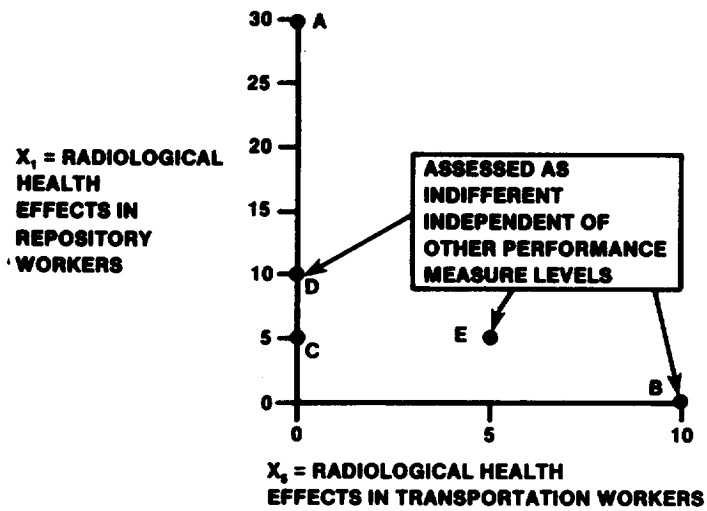

Figure G-5. Verification that $\{X_1, X_5\}$ are preferentially independent of other performance measures.

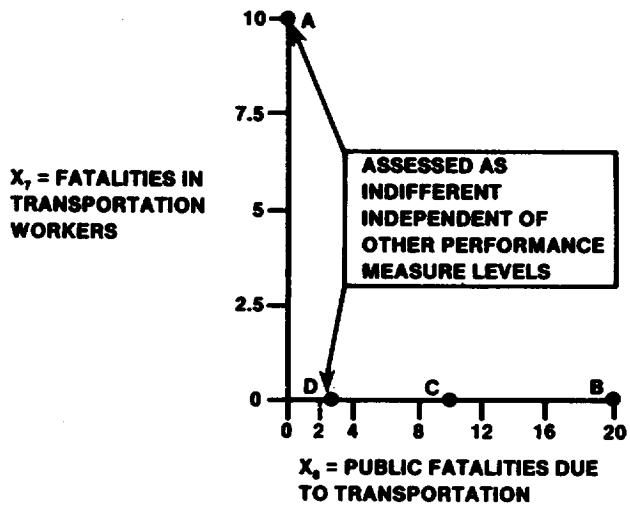

Figure G-6. Verification that $\{X_7, X_8\}$ are preferentially independent of other performance measures.

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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.

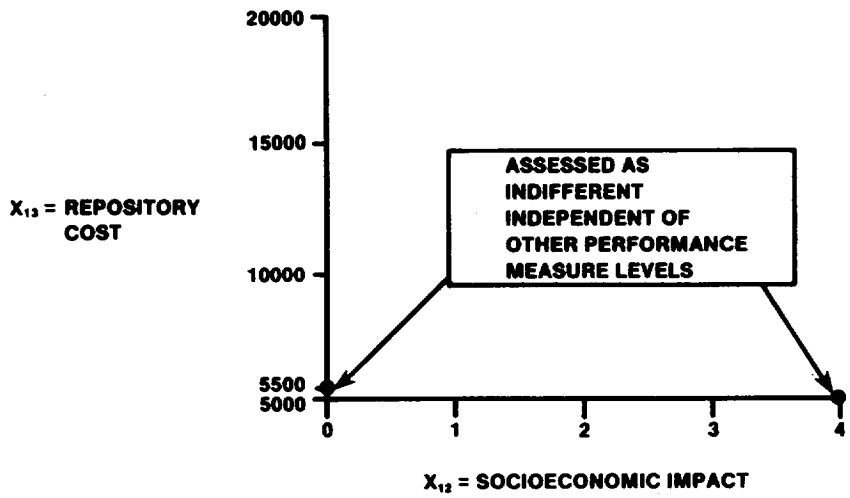

Figure G-7. Verification that $\{X_{12}, X_{13}\}$ are preferentially independent of other performance measures.

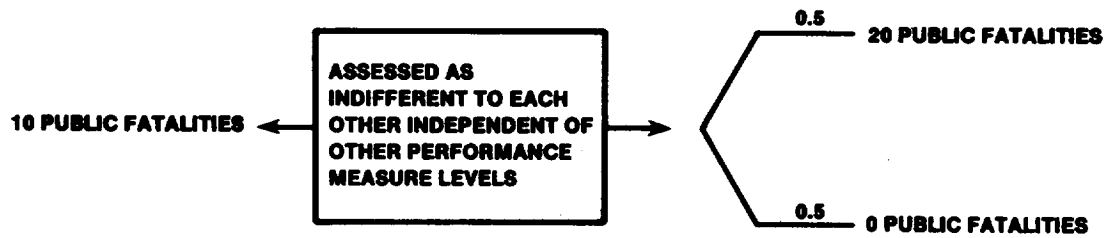

Figure G-8. Verification that X_8, noncancer public fatalities due to transportation, is utility independent of the other performance measures.

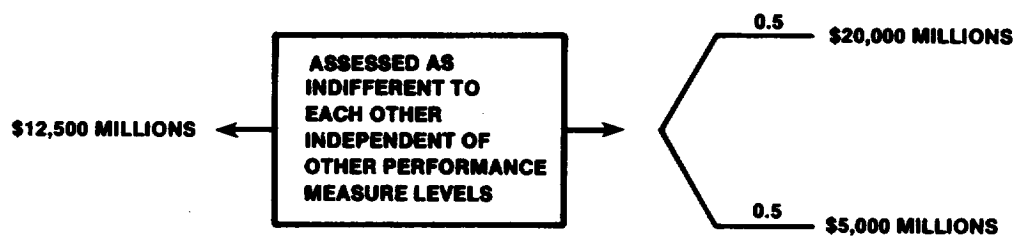

Figure G-9. Verification that X_{13}, repository costs, is utility independent of the other performance measures.

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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.

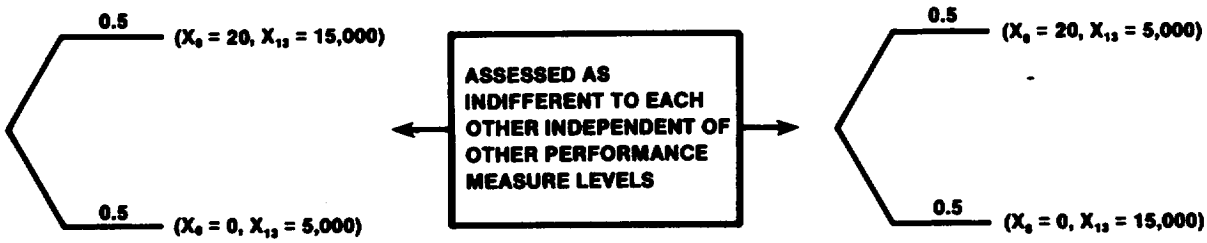

Figure G-10. Verification that X_7, noncancer worker fatalities due to transportation, and X_8, noncancer public fatalities due to transportation, are additive independent.

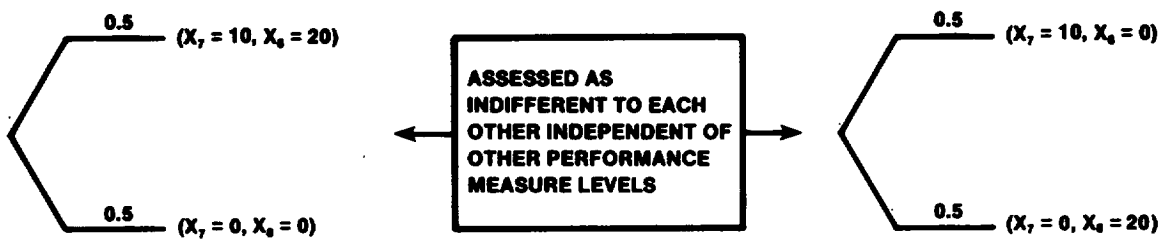

Figure G-11. Verification that X_8, noncancer public fatalities due to transportation, and X_{13}, repository costs, are additive independent.

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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

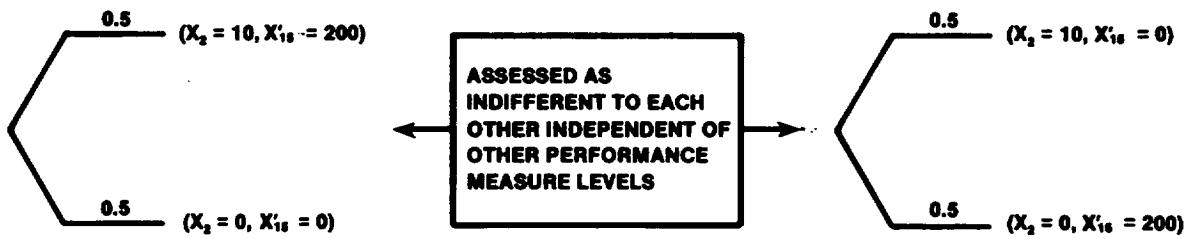

Figure G-12. Verification that X_2, preclosure public health effects due to repository radionuclide releases, and X'_{15}, a measure of postclosure health effects due to reposiotry radionuclide releases in the first 10,000 years, are additive independent.

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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

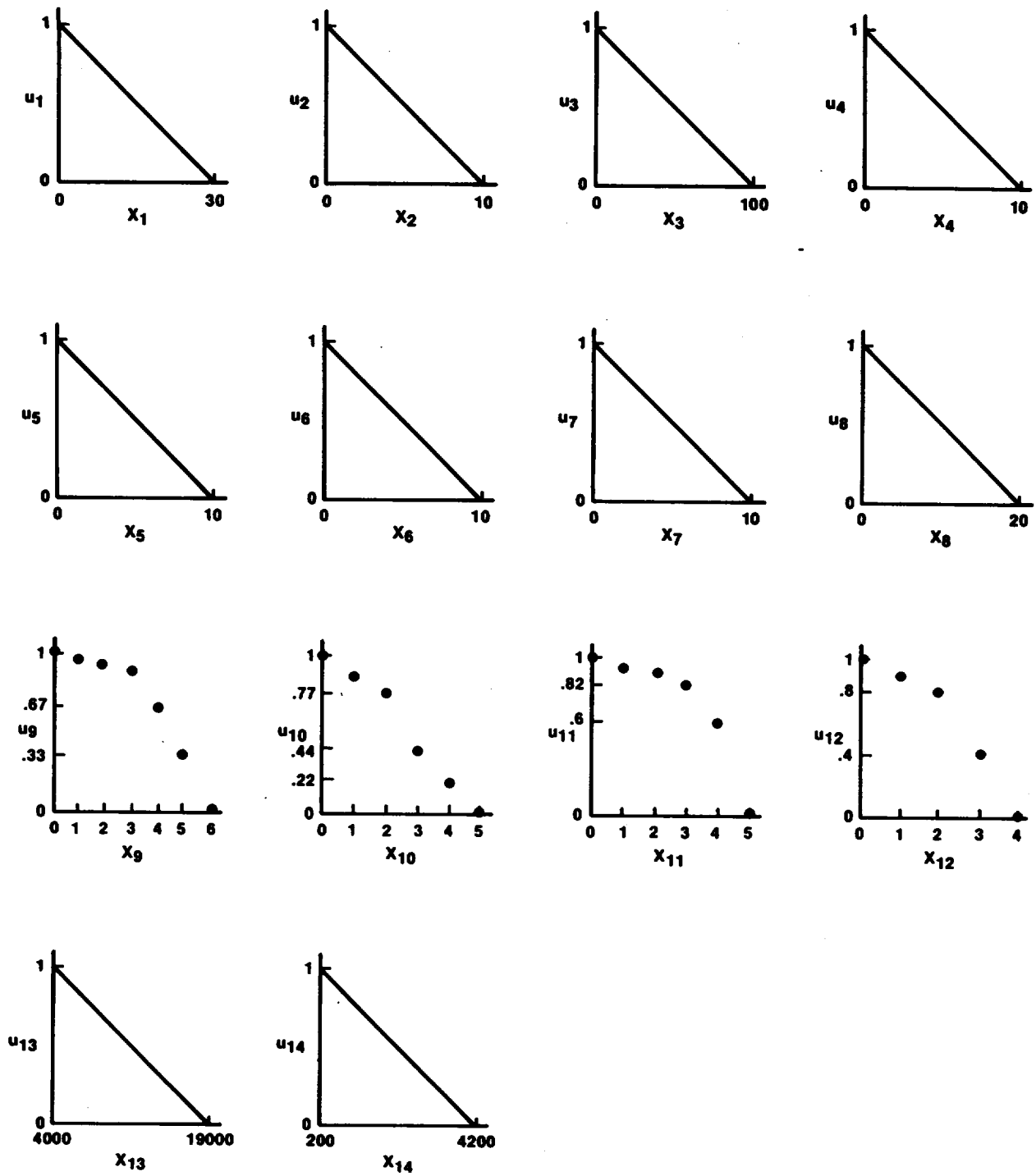

Figure G-13. The assessed component utility functions.

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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 do not 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 not 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

$$u(x) = h - be^{cx} \tag{G-20}$$

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

$$u(x) = h + be^{-cx} \tag{G-21}$$

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

$$U(x_1,\ldots,x_{14}) = A + B\exp[cu(x_1,\ldots,x_{14})], \tag{G-22}$$

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
2101 Constitution Avenue Washington, D.C. 20418

BOARD ON
RADIOACTIVE WASTE MANAGEMENT
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OFFICE LOCATION:
JOSEPH HENRY BUILDING
21ST STREET AND
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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. Park

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.

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

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.

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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 21 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
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OFFICE LOCATION:
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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

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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

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