Title 40 CFR Part 191 Compliance Certification Application for the Waste Isolation Pilot Plant

Appendix SCR

United States Department of Energy
Waste Isolation Pilot Plant

Carlsbad Area Office
Carlsbad, New Mexico

FEPs Screening

CONTENTS

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FIGURES

TABLES

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ACRONYMS

CCDF	complementary cumulative distribution function
CDF	cumulative distribution function
CFR	Code of Federal Regulations
CH	contact-handled
DFR	driving force ratio
DOE	U.S. Department of Energy
DRZ	disturbed rock zone
EDTA	ethylene diamine tetra-acetate
EPA	Environmental Protection Agency
EPs	events and processes
FEPs	features, events, and processes
FLAC	Fast Lagranian Analysis of Continua
LWA	Land Withdrawal Act
MB	marker bed
NMBMMR	New Mexico Bureau of Mines and Mineral Resources
RH	remote-handled
SMC	Salado mass concrete
TRU	transuranic
WAC	Waste Acceptance Criteria
WIPP	Waste Isolation Pilot Plant

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APPENDIX SCR

The methodology used in the Waste Isolation Pilot Plant (WIPP) performance assessments for screening of features, events, and processes (FEPs) is presented in Section 6.2.2 of this application. This appendix presents the results of applying the screening methodology for the analyses that are required to evaluate compliance with the numerical performance requirements provided in Title 40 of the Code of Federal Regulations (CFR) Part 191. This appendix demonstrates comprehensiveness and assembles and organizes relevant decisions and assumptions concerning the phenomena modeled in performance assessments.

Section SCR.1 discusses natural FEPs that are potentially relevant to disposal system[1] performance. Section SCR.2 discusses waste- and repository-induced FEPs. Section SCR.3 discusses human-initiated events and processes (EPs). Key words placed in bold within the text represent FEPs being considered. Section SCR.4 maps retained FEPs into performance assessment codes. Attachment 1 discusses the compilation and construction of the FEP list used in this performance assessment.

SCR.1 Natural FEPs

The natural FEPs discussed in this section are potentially relevant to the analyses conducted to evaluate compliance with the Containment Requirements in 40 CFR § 191.13, the Individual Protection Requirements in 40 CFR § 191.15, and the Groundwater Protection Requirements in 40 CFR § 191.24. While natural FEPs are important to each of these provisions, assessments of compliance with 40 CFR § 191.15 and 40 CFR § 191.24 are based solely upon the undisturbed performance[2] of a disposal system and do not consider disruptions of the disposal system by unlikely natural events.

Unlikely natural events not accounted for in the undisturbed performance of the WIPP are those EPs that have not occurred in the past at a sufficient rate to affect the Salado Formation (hereafter referred to as the Salado) at the repository horizon within the controlled area, or to be expected to cause the release of radionuclides in the regulatory time frame. Further, the U.S. Department of Energy (DOE) believes that, for the WIPP, FEPs eliminated from the performance assessment calculations made to evaluate compliance with 40 CFR § 191.13 can

[1] Note that 40 CFR Part 191 defines the "disposal system" as any combination of engineered and natural barriers that isolates radioactive waste after disposal. Consistent with this definition, the DOE interprets the disposal system to be the repository (excavations, engineered aspects, disturbed rock zone [DRZ]) plus the controlled area, thus incorporating the natural barriers of the controlled area into the disposal system. The definition of the controlled area is provided in 40 CFR § 191.12 and is reproduced in Chapter 6.0.

[2] "Undisturbed performance" is defined in 40 CFR Part 191 to mean "the predicted behavior of a disposal system, including consideration of the uncertainties in predicted behavior, if the disposal system is not disrupted by human intrusion or the occurrence of unlikely natural events" (§ 191.12).

also be eliminated from the undisturbed performance assessment calculations made to evaluate compliance with 40 CFR § 191.15 and 40 CFR § 191.24.

In the remainder of this section, the DOE discusses natural FEPs in the context of the FEP categorization scheme presented in Table SCR-1. The categories concerned with geology (Section SCR.1.1), subsurface hydrology (Section SCR.1.2), and geochemistry (Section SCR.1.3), relate to the subsurface structure, fluid flow, and fluid chemistry, respectively. The categories concerned with geomorphology (Section SCR.1.4), surface hydrology (Section SCR.1.5), climate (Section SCR.1.6), marine environment (Section SCR.1.7), and ecology (Section SCR.1.8), relate to the potential influence of natural FEPs on conditions at and near the ground surface. FEPs presented in Table SCR-1 are printed in bold in the text of the FEP screening discussions.

SCR.1.1 Geological FEPs

SCR.1.1.1 Stratigraphy

The stratigraphy of the geological formations in the region of the WIPP is accounted for in performance assessment calculations. The presence of brine reservoirs in the Castile is accounted for in performance assessment calculations.

The **stratigraphy** and geology of the region around the WIPP, including the distribution and characteristics of pressurized **brine reservoirs** in the Castile Formation (hereafter referred to as the Castile), are discussed in detail in Section 2.1.3. The stratigraphy of the geological formations in the region of the WIPP is accounted for in performance assessment calculations through the setup of the model geometries (Section 6.4.2). The presence of brine reservoirs is accounted for in the treatment of inadvertent drilling (Sections 6.4.12.6 and 6.4.8).

SCR.1.1.2 Tectonics

The effects of regional tectonics, regional uplift and subsidence, and changes in regional stress have been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system.

Regional tectonics encompasses two related issues of concern: the overall level of regional stress and whether any significant **changes in regional stress** might occur.

The tectonic setting and structural features of the area around the WIPP are described in Section 2.1.5. In summary, there is no geological evidence for Quaternary regional tectonics in the Delaware Basin. The eastward tilting of the region has been dated as mid-Miocene to Pliocene by King (1948, 120 – 121) and is associated with the uplift of the Guadalupe Mountains to the west. Fault zones along the eastern margin of the basin, where it flanks the Central Basin Platform, were active during the Late Permian. Evidence for this includes the displacement of the Rustler Formation (hereafter referred to as the Rustler) observed by Holt

Table SCR-1. Natural FEPs and Their Screening Classifications

Features, Events, and Processes (FEPs)	Screening Classification	Comments	Appendix SCR Section
GEOLOGICAL FEPS			SCR.1.1
Stratigraphy			SCR.1.1.1
Stratigraphy	UP		
Brine reservoirs	DP		
Tectonics			SCR.1.1.2
Changes in regional stress	SO-C		
Regional tectonics	SO-C		
Regional uplift and subsidence	SO-C		
Structural FEPs			SCR.1.1.3
Deformation			SCR.1.1.3.1
Salt deformation	SO-P	UP near repository.	
Diapirism	SO-P		
Fracture development			SCR.1.1.3.2
Formation of fractures	SO-P	UP near repository.	
Changes in fracture properties	SO-C	UP near repository.	
Fault movement			SCR.1.1.3.3
Formation of new faults	SO-P		
Fault movement	SO-P		
Seismic activity			SCR.1.1.3.4
Seismic activity	UP		
Crustal processes			SCR.1.1.4
Igneous activity			SCR.1.1.4.1
Volcanic activity	SO-P		
Magmatic activity	SO-C		
Metamorphism			SCR.1.1.4.2
Metamorphic activity	SO-P		
Geochemical FEPs			SCR.1.1.5
Dissolution			SCR.1.1.5.1
Shallow dissolution	UP		
Lateral dissolution	SO-C		
Deep dissolution	SO-P		
Solution chimneys	SO-P		
Breccia pipes	SO-P		
Collapse breccias	SO-P		
Mineralization			SCR.1.1.5.2
Fracture infills	SO-C		
SUBSURFACE HYDROLOGICAL FEPS			SCR.1.2
Groundwater characteristics			SCR.1.2.1
Saturated groundwater flow	UP		
Unsaturated groundwater flow	UP	SO-C in Culebra.	
Fracture flow	UP		
Density effects on groundwater flow	SO-C		
Effects of preferential pathways	UP	UP in Salado and Culebra.	

Table SCR-1. Natural FEPs and Their Screening Classifications (Continued)

Features, Events, and Processes (FEPs)	Screening Classification	Comments	Appendix SCR Section
Changes in groundwater flow			SCR.1.2.2
Thermal effects on groundwater flow	SO-C		
Saline intrusion	SO-P		
Freshwater intrusion	SO-P		
Hydrological response to earthquakes	SO-C		
Natural gas intrusion	SO-P		
SUBSURFACE GEOCHEMICAL FEPS			SCR.1.3
Groundwater geochemistry			SCR.1.3.1
Groundwater geochemistry	UP		
Changes in groundwater chemistry			SCR.1.3.2
Saline intrusion	SO-C		
Freshwater intrusion	SO-C		
Changes in groundwater Eh	SO-C		
Changes in groundwater pH	SO-C		
Effects of dissolution	SO-C		
GEOMORPHOLOGICAL FEPS			SCR.1.4
Physiography			SCR.1.4.1
Physiography	UP		
Meteorite impact			SCR.1.4.2
Impact of a large meteorite	SO-P		
Denudation			SCR.1.4.3
Weathering			SCR.1.4.3.1
Mechanical weathering	SO-C		
Chemical weathering	SO-C		
Erosion			SCR.1.4.3.2
Aeolian erosion	SO-C		
Fluvial erosion	SO-C		
Mass wasting	SO-C		
Sedimentation			SCR.1.4.3.3
Aeolian deposition	SO-C		
Fluvial deposition	SO-C		
Lacustrine deposition	SO-C		
Mass wasting	SO-C		
Soil development			SCR.1.4.4
Soil development	SO-C		
SURFACE HYDROLOGICAL FEPS			SCR.1.5
Fluvial			SCR.1.5.1
Stream and river flow	SO-C		
Lacustrine			SCR.1.5.2
Surface water bodies	SO-C		
Groundwater recharge and discharge			SCR.1.5.3
Groundwater discharge	UP		

Table SCR-1. Natural FEPs and Their Screening Classifications (Continued)

Features, Events, and Processes (FEPs)	Screening Classification	Comments	Appendix SCR Section
Groundwater recharge	UP		
Infiltration	UP	UP for climate change effects.	
Changes in surface hydrology			SCR.1.5.4
Changes in groundwater recharge and discharge	UP		
Lake formation	SO-C		
River flooding	SO-C		
CLIMATIC FEPS			SCR.1.6
Climate			SCR.1.6.1
Precipitation (for example, rainfall)	UP		
Temperature	UP		
Climate change			SCR.1.6.2
Meteorological			SCR.1.6.2.1
Climate change	UP		
Glaciation			SCR.1.6.2.2
Glaciation	SO-P		
Permafrost	SO-P		
MARINE FEPS			SCR.1.7
Seas			SCR.1.7.1
Seas and oceans	SO-C		
Estuaries	SO-C		
Marine sedimentology			SCR.1.7.2
Coastal erosion	SO-C		
Marine sediment transport and deposition	SO-C		
Sea level changes			
Sea level changes	SO-C		SCR.1.7.3
ECOLOGICAL FEPS			SCR.1.8
Flora & fauna			SCR.1.8.1
Plants	SO-C		
Animals	SO-C		
Microbes	SO-C	UP for colloidal effects and gas generation	

Table SCR-1. Natural FEPs and Their Screening Classifications (Continued)

Features, Events, and Processes (FEPs)	Screening Classification	Comments	Appendix SCR Section
Changes in flora & fauna			SCR.1.8.2
Natural ecological development	SO-C		

Legend:

UP FEPs accounted for in the assessment calculations for undisturbed performance for 40 CFR § 191.13 (as well as 40 CFR § 191.15 and Subpart C of 40 CFR Part 191).

DP FEPs accounted for (in addition to all UP FEPs) in the assessment calculations for disturbed performance for 40 CFR § 191.13.

SO-R FEPs eliminated from performance assessment calculations on the basis of regulations provided in 40 CFR Part 191 and criteria provided in 40 CFR Part 194.

SO-C FEPs eliminated from performance assessment (and compliance assessment) calculations on the basis of consequence.

SO-P FEPs eliminated from performance assessment (and compliance assessment) calculations on the basis of low probability of occurrence.

and Powers (1988, 4 – 14; see also Appendix FAC) and the thinning of the Dewey Lake Redbeds (hereafter referred to as the Dewey Lake) reported by Schiel (1994). There is, however, no surface displacement along the trend of these fault zones, indicating that there has been no significant Quaternary movement. Other faults identified within the evaporite sequence of the Delaware Basin are inferred by Barrows' figures in Borns et al. (1983, 58 – 60) to be the result of salt deformation rather than regional tectonic processes. According to Muehlberger et al. (1978, 338), the nearest faults on which Quaternary movement has been identified lie to the west of the Guadalupe Mountains and are of minor regional significance. The effects of regional tectonics and changes in regional stress have therefore been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system.

There are no reported stress measurements from the Delaware Basin, but a low level of regional stress has been inferred from the geological setting of the area (see Section 2.1.5). The inferred low level of regional stress and the lack of Quaternary tectonic activity indicate that regional tectonics and any changes in regional stress will be minor and therefore of low consequence to the performance of the disposal system. Even if rates of regional tectonic movement experienced over the past 10 million years continue, the extent of **regional uplift and subsidence** over the next 10,000 years would only be about several feet (approximately 1 meter). This amount of uplift or subsidence would not lead to a breach of the Salado because the salt would deform plastically to accommodate this slow rate of movement. Uniform regional uplift or a small increase in regional dip consistent with this past rate could give rise to downcutting by rivers and streams in the region. The extent of this downcutting would be little more than the extent of uplift, and reducing the overburden by 1 or 2 meters would have no significant effect on groundwater flow or contaminant transport in units above or below the Salado. Thus, the effects of regional uplift and subsidence have been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system.

SCR.1.1.3 Structural FEPs

SCR.1.1.3.1 Deformation

Natural salt deformation and diapirism at the WIPP site over the next 10,000 years on a scale severe enough to significantly affect performance of the disposal system has been eliminated from performance assessment calculations on the basis of low probability of occurrence.

Deformed salt in the lower Salado and upper strata of the Castile has been encountered in a number of boreholes around the WIPP site; the extent of existing salt deformation is summarized in Section 2.1.6.1, and further detail is provided in Appendix DEF.

A number of mechanisms may result in **salt deformation**: in massive salt deposits, buoyancy effects or **diapirism** may cause salt to rise through denser, overlying units; and in bedded salt with anhydrite or other interbeds, gravity foundering of the interbeds into the halite may take place. Results from rock mechanics modeling studies (see Appendix DEF) indicate that the time scale for the deformation process is such that significant natural deformation is unlikely to occur at the WIPP site over any time frame significant to waste isolation. Thus, natural salt deformation and diapirism severe enough to alter existing patterns of groundwater flow or the behavior of the disposal system over the regulatory period has been eliminated from performance assessment calculations on the basis of low probability of occurrence over the next 10,000 years.

SCR.1.1.3.2 Fracture Development

Naturally induced changes in fracture properties that may affect groundwater flow or radionuclide transport in the region of the WIPP have been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system. The formation of fractures has been eliminated from performance assessment calculations on the basis of a low probability of occurrence over 10,000 years.

Groundwater flow in the region of the WIPP and transport of any released radionuclides may take place along fractures. The rate of flow and the extent of transport will be influenced by fracture characteristics such as orientation, aperture, asperity, fracture length and connectivity, and the nature of any linings or infills. These characteristics are accounted for in the performance assessment calculations through the description of the hydrogeological properties of the transmissive units (Sections 2.2.1 and 6.4.6.2).

Dissolution and precipitation of minerals in fractures are discussed in Sections SCR.1.1.5.1 and SCR.1.1.5.2, respectively. **Changes in fracture properties** could also arise through natural changes in the local stress field, for example, through erosion or sedimentation changing the amount of overburden (see Sections SCR.1.4.3.2 and SCR.1.4.3.3). The extent of natural changes in stress is expected to be small, and naturally induced changes in fractures that may affect groundwater flow or radionuclide transport in the region of the WIPP, therefore, have been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system.

The **formation of fractures** requires larger changes in stress than are required for changes to the properties of existing fractures to overcome the shear and tensile strength of the rock. The regional tectonic setting of the Delaware Basin is described in Section 2.1.5. It is concluded that no significant changes in regional stress are expected over the regulatory period (see also Section SCR.1.1.2). The formation of new fracture sets has therefore been eliminated from performance assessment calculations on the basis of a low probability of occurrence over 10,000 years.

Repository-induced fracturing of the DRZ and Salado interbeds is accounted for in performance assessment calculations, and is discussed in Section SCR.2.3.1.

SCR.1.1.3.3 *Fault Movement*

The naturally induced formation of new faults and fault movement of sufficient magnitude to significantly affect the performance of the disposal system have been eliminated from performance assessment calculations on the basis of low probability of occurrence over 10,000 years.

Faults are present in the Delaware Basin in both the units underlying the Salado and in the Permian evaporite sequence (see Section 2.1.5.2). According to Powers et al. (1978, 4 – 57, included as Appendix GCR), there is evidence that movement along faults within the pre-Permian units affected the thickness of Early Permian strata, but these faults did not exert a structural control on the deposition of the Castile, the Salado, or the Rustler. Fault zones along the margins of the Delaware Basin were active during the Late Permian Period. Along the eastern margin, where the Delaware Basin flanks the Central Basin Platform, Holt and Powers (Appendix FAC, 4 – 14) note that there is displacement of the Rustler, and Schiel (1994) notes that there is thinning of the Dewey Lake. There is, however, no surface displacement along the trend of these fault zones, indicating that there has been no significant Quaternary movement. Muehlberger et al. (1978, 338) note that the nearest faults on which Quaternary movement has been identified lie to the west of the Guadalupe Mountains.

The absence of Quaternary fault scarps and the general tectonic setting and understanding of its evolution indicate that large-scale, tectonically-induced **fault movement** within the Delaware Basin can be eliminated from performance assessment calculations on the basis of low probability over 10,000 years. The stable tectonic setting also allows the **formation of new faults** within the basin over the next 10,000 years to be eliminated from performance assessment calculations on the basis of low probability of occurrence.

Subsidence above natural dissolution features could lead to the formation of, and movement along, local faults. However, significant dissolution in the region of the waste panels has been eliminated from performance assessment calculations on the basis of low probability of occurrence over 10,000 years (see Section SCR.1.1.5.1), so faults arising from dissolution have also been eliminated on the basis of low probability of occurrence.

SCR.1.1.3.4 *Seismic Activity*

The postclosure effects of seismic activity on the repository and the DRZ are accounted for in performance assessment calculations.

This section is concerned with the effects of seismic activity away from the immediate source region, and only the effects of groundshaking and earthquakes are discussed. Other sections discuss the direct effects of fault movement (SCR.1.1.3.3), and changes in hydrogeology induced by seismic activity (SCR.1.2.2.5).

SCR.1.1.3.4.1 Causes of Seismic Activity

Seismic activity describes transient ground motion that may be generated by several energy sources. There are two possible causes of seismic activity that could potentially affect the WIPP site: natural and human induced. Natural seismic activity is caused by fault movement (earthquakes) when the buildup of strain in rock is released through sudden rupture or movement. Human-induced seismic activity may result from a variety of surface and subsurface activities, such as explosions, mining, fluid injection, and fluid withdrawal that are discussed in Section SCR.3.

SCR.1.1.3.4.2 Groundshaking

Ground vibration and the consequent shaking of buildings and other structures are the most obvious effects of seismic activity. Once the repository and shafts have been sealed, however, existing surface structures will be dismantled. Postclosure performance assessments are concerned with the effects of seismic activity on the closed repository.

In regions of low and moderate seismic activity, such as the Delaware Basin, rocks behave elastically in response to the passage of seismic waves, and there are no long-term changes in rock properties, and the effects of earthquakes beyond the DRZ have been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system. An inelastic response, such as cracking, is only possible where there are free surfaces, as in the roof and walls of the repository prior to closure by creep. **Seismic activity** could, therefore, have an effect on the properties of the DRZ.

An assessment of the extent of damage in underground excavations caused by groundshaking largely depends on observations from mines and tunnels. Because such excavations tend to take place in rock types more brittle than halite, these observations cannot be related directly to the behavior of the WIPP. According to Wallner (1981, 244), the DRZ in brittle rock types is likely to be more highly fractured and hence more prone to spalling and rockfalls than an equivalent zone in salt. Relationships between groundshaking and subsequent damage observed in mines will therefore be conservative with respect to the extent of damage induced at the WIPP by seismic activity.

Dowding and Rozen (1978) classified damage in underground structures following seismic activity and found that no damage (cracks, spalling, or rockfalls) occurred at accelerations below 0.2 gravities and that only minor damage occurred at accelerations up to 0.4 gravities. Lenhardt (1988, 392) showed that a magnitude 3 earthquake would have to be within 0.6 mile (1 kilometer) of a mine to result in falls of loose rock. The risk of seismic activity in the region of the WIPP reaching these thresholds is discussed below.

SCR.1.1.3.4.3 Seismic Risk in the Region of the WIPP

Prior to the introduction of a seismic monitoring network in 1960, most recorded earthquakes in New Mexico were associated with the Rio Grande Rift, although small earthquakes were detected in other parts of the region. In addition to continued activity in the Rio Grande Rift, the instrumental record has shown a significant amount of seismic activity originating from the Central Basin Platform and a number of small earthquakes in the Los Medaños area. Seismic activity in the Rio Grande Rift is associated with extensional tectonics in that area. Seismic activity in the Central Basin Platform may be associated with natural earthquakes, but there are also indications that this activity occurs in association with oil-field activities such as fluid injection. Small earthquakes in the Los Medaños region have not been precisely located, but may be the result of mining activity in the region. Section 2.6.2 contains additional discussion of seismic activity and risk in the WIPP region.

The instrumental record was used as the basis of a seismic risk study primarily intended for design calculations of surface facilities rather than for postclosure performance assessments. The use of this study to define probable ground accelerations in the WIPP region over the next 10,000 years is based on the assumptions that hydrocarbon extraction and potash mining will continue in the region and that the regional tectonic setting precludes major changes over the next 10,000 years.

Three source regions were used in calculating seismic risk: the Rio Grande Rift, the Central Basin Platform, and part of the Delaware Basin province (including the Los Medaños). Using conservative assumptions about the maximum magnitude event in each zone, the study indicated a return period of about 10,000 years (annual probability of occurrence of 10^{-4}) for events producing ground accelerations of 0.1 gravities. Ground accelerations of 0.2 gravities would have an annual probability of occurrence of about 5×10^{-6}.

The results of the seismic risk study and the observations of damage in mines due to groundshaking, give an estimated annual probability of occurrence of between 10^{-6} and 10^{-8} for events that could increase the permeability of the DRZ. The DRZ is accounted for in performance assessment calculations as a zone of permanently high permeability (see Section 6.4.5.3); this treatment is considered to account for the effects of any potential seismic activity.

SCR.1.1.4 Crustal Processes

SCR.1.1.4.1 Igneous Activity

Volcanic activity has been eliminated from performance assessment calculations on the basis of low probability of occurrence over 10,000 years. The effects of magmatic activity have been eliminated from the performance assessment calculations on the basis of low consequence to the performance of the disposal system.

SCR.1.1.4.1.1 Volcanic Activity

The Paleozoic and younger stratigraphic sequences within the Delaware Basin are devoid of locally derived volcanic rocks. Volcanic ashes (dated at 13 million years and 0.6 million year) do occur in the Gatuña Formation (hereafter referred to as the Gatuña), but these are not locally derived. Within eastern New Mexico and northern, central, and western Texas, the closest Tertiary volcanic rocks with notable areal extent or tectonic significance to the WIPP are approximately 100 miles (160 kilometers) to the south in the Davis Mountains volcanic area. The closest Quaternary volcanic rocks are 150 miles (250 kilometers) to the northwest in the Sacramento Mountains. No volcanic rocks are exposed at the surface within the Delaware Basin.

Volcanic activity is associated with particular tectonic settings: constructive and destructive plate margins, regions of intraplate rifting, and isolated hot-spots in intraplate regions. The tectonic setting of the WIPP site and the Delaware Basin is remote from plate margins, and the absence of past volcanic activity indicates the absence of a major hot spot in the region. Intraplate rifting has taken place along the Rio Grande some 120 miles (200 kilometers) west of the WIPP site during the Tertiary and Quaternary Periods. Igneous activity along this rift valley is comprised of sheet lavas intruded on by a host of small-to-large plugs, sills, and other intrusive bodies. However, the geological setting of the WIPP site within the large and stable Delaware Basin allows volcanic activity in the region of the WIPP repository to be eliminated from performance calculations on the basis of low probability of occurrence over the next 10,000 years.

SCR.1.1.4.1.2 Magmatic Activity

Magmatic activity is defined as the subsurface intrusion of igneous rocks into country rock. Deep intrusive igneous rocks crystallize at depths of several kilometers and have no surface or near-surface expression until considerable erosion has taken place. Alternatively, intrusive rocks may form from magma that has risen to near the surface or in the vents that give rise to volcanoes and lava flows. Magma near the surface may be intruded along subvertical and subhorizontal discontinuities (forming dikes and sills, respectively), and magma in volcanic vents may solidify as plugs. The formation of such features close to a repository or the existence of a recently intruded rock mass could impose thermal stresses inducing new fractures or altering the hydraulic characteristics of existing fractures.

The principal area of magmatic activity in New Mexico is the Rio Grande Rift, where extensive intrusions occurred during the Tertiary and Quaternary Periods. The Rio Grande Rift, however, is in a different tectonic province than the Delaware Basin, and its magmatic activity is related to the extensional stress regime and high heat flow in that region.

Within the Delaware Basin, there is a single identified outcrop of a lamprophyre dike about 40 miles (70 kilometers) southwest of the WIPP (see Section 2.1.5.4 and Appendix GCR for more detail). Closer to the WIPP site, similar rocks have been exposed within potash mines some 10 miles (15 kilometers) to the northwest, and igneous rocks have been reported from petroleum exploration boreholes. Material from the subsurface exposures has been dated at around 35 million years. Some recrystallization of the host rocks took place alongside the intrusion, and there is evidence that minor fracture development and fluid migration also occurred along the margins of the intrusion. However, the fractures have been sealed, and there is no evidence that the dike acted as a conduit for continued fluid flow.

Aeromagnetic surveys of the Delaware Basin have shown anomalies that lie on a linear southwest-northeast trend that coincides with the surface and subsurface exposures of magmatic rocks. There is a strong indication therefore of a dike or a closely related set of dikes extending for at least 70 miles (120 kilometers) across the region (see Section 2.1.5.4). The aeromagnetic survey conducted to delineate the dike showed a magnetic anomaly that is several miles (several kilometers) wide at depth and narrows to a thin trace near the surface. This pattern is interpreted as the result of an extensive dike swarm at depths of less than 2.5 miles (approximately 4.0 kilometers) near the Precambrian basement, from which a limited number of dikes have extended towards the surface.

Magmatic activity has taken place in the vicinity of the WIPP site in the past, but the igneous rocks have cooled over a long period. Any enhanced fracturing or conduits for fluid flow have been sealed by salt creep and mineralization. Continuing magmatic activity in the Rio Grande Rift is too remote from the WIPP location to be of consequence to the performance of the disposal system. Thus, the effects of magmatic activity have been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system.

SCR.1.1.4.2 Metamorphism

Metamorphic activity has been eliminated from performance assessment calculations on the basis of low probability of occurrence over the next 10,000 years.

Metamorphic activity, that is, solid state recrystallization changes to rock properties and geologic structures through the effects of heat and/or pressure, requires depths of burial much greater than the depth of the repository. Regional tectonics that would result in the burial of the repository to the depths at which the repository would be affected by metamorphic activity have been eliminated from performance assessment calculations on the basis of low probability of occurrence; therefore, metamorphic activity has also been eliminated from performance assessment calculations on the basis of low probability of occurrence over the next 10,000 years.

SCR.1.1.5 Geochemical FEPs

SCR.1.1.5.1 Dissolution

Shallow dissolution is accounted for in performance assessment calculations. Deep dissolution and the formation of associated features (for example, solution chimneys, breccia pipes, collapse breccias) at the WIPP site have been eliminated from performance assessment calculations on the basis of low probability of occurrence over the next 10,000 years. Lateral dissolution has been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system.

This section discusses a variety of styles of dissolution that have been active in the region of the WIPP or in the Delaware Basin. A distinction has been drawn between **shallow dissolution**, involving percolation of groundwater and mineral dissolution in the Rustler; **lateral dissolution**, involving dissolution at the top of the Salado; and **deep dissolution** taking place in the Castile and the base of the Salado. Dissolution will initially enhance porosities, but continued dissolution may lead to compaction of the affected units with a consequent reduction in porosity. Compaction may result in fracturing of overlying brittle units and increased permeability. Extensive dissolution may create cavities (karst) and result in the total collapse of overlying units. This topic is discussed further in Section 2.1.6.2.

SCR.1.1.5.1.1 Shallow Dissolution

Flow through fractures is an important contributor to groundwater flow in the Culebra and other units of the Rustler, and the conductivity of fractures is the principal control of this flow. East of the WIPP site, a significant proportion of the fractures within the Culebra are infilled with secondary gypsum (see Figure 2-12), whereas to the west of the site most fractures are open. This distribution of infilled fractures closely parallels the spatial variability of lateral transmissivity in the Culebra (Figure 2-30) and is accounted for in performance assessment calculations through the use of geostatistically conditioned transmissivity fields (Section 6.4.6.2).

Groundwater basin modeling indicates that the Culebra becomes progressively more confined toward the east. This corresponds to an increase in the overburden towards the east and a decrease in the fracturing associated with dissolution at the Rustler - Salado boundary. The analysis presented below indicates that the lateral extent of dissolution at the top of the Salado is not expected to reach the edge of the controlled area for some 225,000 years, and the rates of erosion in this region (see Section SCR.1.4.3.2) are very low. The pattern of vertical transmissivity in the Rustler is therefore not expected to change significantly during the next 10,000 years, and neither the degree of confinement of the Culebra nor the pattern of open fractures in this unit will undergo significant change during this period.

Percolating groundwater will result in some dissolution and precipitation of fracture infills over the next several climate cycles. The present pattern of secondary gypsum in fractures within the Culebra is considered to be the result of changes in precipitation and recharge over many climate cycles and a similar degree of spatial variability is anticipated to persist into the future. The pattern of secondary gypsum is not considered to be the result of progressive movement of a dissolution front across the area, and the extent of changes in lateral transmissivity in the Culebra will be within the degree of uncertainty accounted for by the use of conditioned transmissivity fields.

Thus, the existing features associated with shallow dissolution and changes due to further shallow dissolution are accounted for in performance assessment calculations through the use of multiple transmissivity fields.

SCR.1.1.5.1.2 Lateral Dissolution

Lateral dissolution takes place when percolating groundwater dissolves halite at the top of the Salado, causing collapse of the overlying Rustler with consequent changes in hydrogeological properties. Nash Draw, some 5 miles (8 kilometers) to the west of the WIPP site, is the most prominent lateral dissolution feature in the region. An average lateral dissolution rate of from 6 to 8 miles (10 to 13 kilometers) per million years has been calculated by Bachman et al. (1973, 39) for the Salado based on the assumption that the edge of the salt has moved from the Capitan Reef to its present position over the past 7 to 8 million years. A vertical dissolution rate of 0.06 mile (0.1 kilometer) per million years has similarly been calculated by Bachman (1974, 71; 1980, 97; 1981, 3) using dated ash layers. Although these are average rates and may be exceeded during particular climate states or by advancing tongues ahead of the main dissolution front, these rates indicate that dissolution of the Salado at the edge of the WIPP site would not take place for some 225,000 years, and an additional 2 to 3 million years would be required for dissolution to reach the repository horizon.

Lateral dissolution may also have affected the Rustler directly. In the vicinity of Nash Draw, halite is absent from all the units of the Rustler. Further east, towards the WIPP site, halite progressively appears in younger units. This has led many investigators to conclude that halite has been dissolved from the Rustler by groundwater (see, for example, Lambert 1983, Bachman 1984, and Lowenstein 1987). A sedimentological analysis of the Rustler in 1988 led Holt and Powers (Appendix FAC) to conclude that halite had either not been formed or had dissolved soon after deposition and, therefore, that only limited lateral dissolution has occurred since Permian times. Even if post-depositional dissolution has taken place, the period over which it occurred is longer than the regulatory period. Lateral dissolution has therefore been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system.

SCR.1.1.5.1.3 Deep Dissolution

Deep dissolution refers to the dissolution of salt or other evaporite minerals in a formation at depth (see Section 2.1.6.2). Deep dissolution is distinguished from shallow and lateral dissolution not only by depth, but also by the origin of the water. Dissolution by groundwater from deep water-bearing zones can lead to the formation of cavities. Collapse of overlying beds leads to the formation of **collapse breccias** if the overlying rocks are brittle or to deformation if the overlying rocks are ductile. If dissolution is extensive, **breccia pipes** or **solution chimneys** may form above the cavity. These pipes may reach the surface or pass upwards into fractures and then into microcracks that do not extend to the surface. Breccia pipes may also form through the downward percolation of meteoric waters, as discussed earlier. Deep dissolution is of concern because it could accelerate contaminant transport through the creation of vertical flow paths that bypass low-permeability units in the Rustler. If dissolution occurred within or beneath the waste panels themselves, there could be increased circulation of groundwater through the waste as well as a breach of the Salado host rock.

Features identified as being the result of deep dissolution are present along the northern and eastern margins of the Delaware Basin. In addition to features that have a surface expression or that appear within potash mine workings, deep dissolution has been cited by Anderson et al. (1972, 81) as the cause of lateral variability within evaporite sequences in the lower Salado. Observations concerning various features ascribed to deep dissolution are considered in the following subsections.

SCR.1.1.5.1.4 Solution Chimneys

Exposures of the McNutt Potash Member of the Salado within a mine near Nash Draw have shown a solution pipe containing cemented brecciated fragments of formations higher in the stratigraphic sequence. At the surface, this feature is marked by a dome, and similar domes have been interpreted as dissolution features. The depth of dissolution has not been confirmed, but the collapse structures led Anderson (1978, 52) and Snyder et al. (1982, 65) to postulate dissolution of the Capitan Limestone at depth; collapse of the Salado, Rustler, and younger formations; and subsequent dissolution and hydration by downward percolating waters. San Simon Sink (see Section 2.1.6.2), some 20 miles (35 kilometers) east-southeast of the WIPP site, has also been interpreted as a solution chimney. Subsidence has occurred there in historical times according to Nicholson and Clebsch (1961, 14), suggesting that dissolution at depth is still taking place. Whether this is the result of downwards-percolating surface water or of deep groundwater has not been confirmed. The association of these dissolution features with the inner margin of the Capitan Reef suggest that they owe their origins, if not their continued development, to groundwaters derived from the Capitan Limestone.

SCR.1.1.5.1.5 Dissolution within the Castile and Lower Salado Formations

The Castile contains sequences of varved anhydrite and carbonate (that is, laminae deposited on a cyclical basis) that can be correlated between several boreholes. On the basis of these deposits, a basin-wide uniformity in the depositional environment of the Castile evaporites was assumed. The absence of varves from all or part of a sequence and the presence of brecciated anhydrite beds have been interpreted by Anderson et al. (1972) as evidence of dissolution. Holt and Powers (Appendix FAC) have questioned the assumption of a uniform depositional environment and contend that the anhydrite beds are lateral equivalents of halite sequences without significant postdepositional dissolution. Wedges of brecciated anhydrite along the margin of the Castile have been interpreted by Robinson and Powers (1987, 78) as gravity-driven clastic deposits, rather than the result of deep dissolution.

Localized depressions at the top of the Castile and inclined geophysical marker units at the base of the Salado have been interpreted by Davies (1983, 45) as the result of deep dissolution and subsequent collapse or deformation of overlying rocks. The postulated cause of this dissolution was circulation of undersaturated groundwaters from the Bell Canyon Formation (hereafter referred to as the Bell Canyon). Additional boreholes (notably WIPP-13, WIPP-32, and DOE-2) and geophysical logging led Borns and Shaffer (1985) to conclude that the features interpreted by Davies as being dissolution features are the result of irregularities at the top of the Bell Canyon. These irregularities led to localized depositional thickening of the Castile and lower Salado sediments.

SCR.1.1.5.1.6 Collapse Breccias at Basin Margins

Collapse breccias are present at several places around the margins of the Delaware Basin. Their formation is attributed to relatively fresh groundwater from the Capitan Limestone that forms the margin of the basin. Collapse breccias corresponding to features on geophysical records that have been ascribed to deep dissolution have not been found in boreholes away from the margins. These features have been reinterpreted as the result of early dissolution prior to the deposition of the Salado. This topic is discussed further in Section 2.1.6.2.

SCR.1.1.5.1.7 Summary of Deep Dissolution

Deep dissolution features have been identified within the Delaware Basin, but only in marginal areas underlain by Capitan Reef. There is a low probability that deep dissolution will occur sufficiently close to the waste panels over the regulatory period to affect groundwater flow in the immediate region of the WIPP. Deep dissolution at the WIPP site has therefore been eliminated from performance assessment calculations on the basis of low probability of occurrence over the next 10,000 years.

SCR.1.1.5.2 Mineralization

The effects of fracture infills have been eliminated from performance assessment calculations on the basis of beneficial consequence to the performance of the disposal system.

Precipitation of minerals as **fracture infills** can reduce hydraulic conductivities. The distribution of infilled fractures in the Culebra closely parallels the spatial variability of lateral transmissivity in the Culebra (see Section SCR.1.1.5.1). The secondary gypsum veins in the Rustler have not been dated. Strontium isotope studies (Siegel et al. 1991, 5-53 to 5-57) indicate that the infilling minerals are locally derived from the host rock rather than extrinsically derived, and it is inferred that they reflect an early phase of mineralization and are not associated with recent meteoric waters.

Stable isotope geochemistry in the Rustler has also provided information on mineral stabilities in these strata. Both Chapman (1986, 31) and Lambert and Harvey (1987, 207) imply that the mineralogical characteristics of units above the Salado have been stable or subject to only minor changes under the various recharge conditions that have existed during the past 0.6 million year—the period since the formation of the Mescalero caliche and the establishment of a pattern of climate change and associated changes in recharge that led to present-day hydrogeological conditions. No changes in climate are expected other than those experienced during this period, and for this reason, no changes are expected in the mineralogical characteristics other than those expressed by the existing variability of fracture infills and diagenetic textures. Formation of fracture infills will reduce transmissivities and will therefore be of beneficial consequence to the performance of the disposal system.

SCR.1.2 Subsurface Hydrological FEPs

This section discusses FEPs relating to the natural groundwater system at the WIPP site and FEPs that may lead to changes in its flow and chemical characteristics.

SCR.1.2.1 Groundwater Characteristics

Saturated groundwater flow, unsaturated groundwater flow, fracture flow, and the effects of preferential pathways are accounted for in performance assessment calculations. Density effects on groundwater flow have been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system.

Saturated groundwater flow, **unsaturated groundwater flow**, and **fracture flow** are accounted for in performance assessment calculations. Groundwater flow is discussed in Sections 2.2.1, 6.4.5, and 6.4.6.

The most transmissive unit in the Rustler, and hence the most significant potential pathway for transport of radionuclides to the accessible environment, is the Culebra. The properties of Culebra groundwaters are not homogeneous, and spatial variations in groundwater density

(Section 2.2.1.4.1.2) could influence the rate and direction of groundwater flow. A comparison of the gravity-driven flow component and the pressure-driven component in the Culebra, however, shows that only in the region to the south of the WIPP are head gradients low enough for density gradients to be significant (Davies 1989, 53). Accounting for this variability would rotate groundwater flow vectors towards the east (down-dip) and hence fluid in the high transmissivity zone would move away from the zone. Excluding brine density variations within the Culebra from performance assessment calculations is therefore a conservative assumption, and **density effects on groundwater flow** have been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system.

The hydrogeologic properties of the Culebra are also spatially variable. This variability, including the **effects of preferential pathways**, is accounted for in performance assessment calculations in the estimates of transmissivity and aquifer thickness.

SCR.1.2.2 Changes in Groundwater Flow

Changes in groundwater flow arising from saline intrusion, freshwater intrusion, or natural gas intrusion have been eliminated from performance assessment calculations on the basis of a low probability of occurrence over 10,000 years. Natural thermal effects on groundwater flow have been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system. A hydrological response to earthquakes has been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system.

SCR.1.2.2.1 Saline Intrusion

No natural events or processes have been identified that could result in **saline intrusion** into units above the Salado or cause a significant increase in fluid density. Natural saline intrusion has therefore been eliminated from performance assessment calculations on the basis of low probability of occurrence over the next 10,000 years. Saline intrusion arising from human-initiated events such as drilling into a pressurized brine pocket is discussed in Section SCR.3.3.

SCR.1.2.2.2 Freshwater Intrusion

A number of FEPs, including climate change, can result in changes in infiltration and recharge (see Section SCR.1.5.3). These changes will affect the height of the water table and hence could affect groundwater flow in the Rustler through changes in head gradients. The generally low transmissivity of the Dewey Lake and the Rustler, however, will prevent any significant changes in groundwater density from occurring within the Culebra over the timescales for which increased precipitation and recharge are anticipated. No other natural events or processes have been identified that could result in **freshwater intrusion** into units above the Salado or cause a significant decrease in fluid density. Freshwater intrusion has therefore been eliminated from performance assessment calculations on the basis of low probability of occurrence over the next 10,000 years.

SCR.1.2.2.3 *Thermal Effects*

The geothermal gradient in the region of the WIPP has been measured at about 50°C per mile (30°C per kilometer). Given the generally low permeability in the region, and the limited thickness of units in which groundwater flow occurs (for example the Culebra), natural convection will be too weak to have a significant effect on groundwater flow. No natural FEPs have been identified that could significantly alter the temperature distribution of the disposal system or give rise to **thermal effects on groundwater flow**. Such effects have therefore been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system.

SCR.1.2.2.4 *Natural Gas Intrusion*

Hydrocarbon resources are present in formations beneath the WIPP (Section 2.3.1.2), and natural gas is extracted from the Morrow Formation. These reserves are, however, some 14,000 feet (4,200 meters) below the surface, and no natural events or processes have been identified that could result in **natural gas intrusion** into the Salado or the units above. Natural gas intrusion has therefore been eliminated from performance assessment calculations on the basis of low probability of occurrence over the next 10,000 years.

SCR.1.2.2.5 *Hydrological Effects of Seismic Activity*

There are a variety of **hydrological responses to earthquakes**. Some of these responses, such as changes in surface-water flow directions, result directly from fault movement. Others, such as changes in subsurface water chemistry and temperature, probably result from changes in flow pathways along the fault or fault zone. According to Bredehoeft et al. (1987, 139), further away from the region of fault movement two types of changes to groundwater levels may take place as a result of changes in fluid pressure:

- The passage of seismic waves through a rock mass causes a volume change, inducing a transient response in the fluid pressure, which may be observed as a short-lived fluctuation of the water level in wells.

- Changes in volume strain can cause long-term changes in water level. A buildup of strain occurs prior to rupture and is released during an earthquake. The consequent change in fluid pressure may be manifested by the drying up or reactivation of springs some distance from the region of the epicenter.

Fluid pressure changes induced by the transmission of seismic waves can produce changes of up to several meters in groundwater levels in wells, even at distances of thousands of kilometers from the epicenter. These changes are temporary, however, and levels typically return to pre-earthquake levels in a few hours or days. Changes in fluid pressure arising from changes in volume strain persist for much longer periods, but they are only potentially consequential in tectonic regimes where there is a significant buildup of strain. The regional tectonics of the Delaware Basin indicate that such a buildup has a low probability of occurring over the next 10,000 years (Section SCR.1.1.2).

The expected level of seismic activity in the region of the WIPP will be of low consequence to the performance of the disposal system in terms of groundwater flow or contaminant transport. Changes in groundwater levels resulting from more distant earthquakes will be too short in duration to be significant. Thus, the hydrological effects of earthquakes have been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system.

SCR.1.3 Subsurface Geochemical FEPs

SCR.1.3.1 Groundwater Geochemistry

Groundwater geochemistry in the hydrological units of the disposal system is accounted for in performance assessment calculations.

The most important aspect of **groundwater geochemistry** in the region of the WIPP in terms of chemical retardation and colloid stability is salinity. Groundwater geochemistry is discussed in detail in Sections 2.2 and 2.4 and summarized here. The Delaware Mountain Group, Castile, and Salado contain basinal brines. Waters in the Castile and Salado are at or near halite saturation. Above the Salado, groundwaters are also relatively saline, and groundwater quality is poor in all of the permeable units. Waters from the Culebra vary spatially in salinity and chemistry. They range from saline sodium chloride-rich waters to brackish calcium sulfate-rich waters. In addition, a range of magnesium to calcium ratios has been observed, and some waters reflect the influence of potash mining activities, having elevated potassium to sodium ratios. Waters from the Santa Rosa are generally of better quality than any of those from the Rustler. Salado and Castile brine geochemistry is accounted for in performance assessment calculations of the actinide source term (Section 6.4.3.4). Culebra brine geochemistry is accounted for in the retardation factors used in performance assessment calculations of actinide transport (see Section 6.4.6.2).

SCR.1.3.2 Changes in Groundwater Chemistry

The effects of saline or freshwater intrusion and of dissolution on groundwater chemistry have been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system. Changes in groundwater Eh and pH have been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system.

Natural changes in the groundwater chemistry of the Culebra and other units that resulted from **saline intrusion** or **freshwater intrusion** could potentially affect chemical retardation and the stability of colloids. **Changes in groundwater Eh** and **groundwater pH** could also affect the migration of radionuclides (see Sections SCR.2.5.5 and SCR.2.5.6). No natural events or processes have been identified that could result in saline intrusion into units above the Salado, and the magnitude of any natural temporal variation due to the **effects of dissolution** on groundwater chemistry, or due to changes in recharge is likely to be no greater than the present spatial variation. These FEPs related to the effects of future natural changes in groundwater chemistry have been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system.

SCR.1.4 Geomorphological FEPs

SCR.1.4.1 Physiography

Relevant aspects of the physiography, geomorphology, and topography of the region around the WIPP are accounted for in performance assessment calculations.

Physiography and geomorphology are discussed in detail in Section 2.1.4, and are accounted for in the setup of the performance assessment calculations (Section 6.4.2).

SCR.1.4.2 Meteorite Impact

Disruption arising from the impact of a large meteorite has been eliminated from performance assessment calculations on the basis of low probability of occurrence over 10,000 years.

Meteors frequently enter the earth's atmosphere, but most of these are small and burn up before reaching the ground. Of those that reach the ground, most produce only small impact craters that would have no effect on the postclosure integrity of a repository 2,150 feet (650 meters) below the ground surface. While the depth of a crater may be only one-eighth of its diameter, the depth of the disrupted and brecciated material is typically one-third of the overall crater diameter (Grieve 1987, 248). Direct disruption of waste at the WIPP would only occur with a crater larger than 1.1 miles (1.8 kilometers) in diameter. Even if waste were not directly disrupted, the **impact of a large meteorite** could create a zone of fractured rocks beneath and around the crater. The extent of such a zone would depend on the rock type. For sedimentary rocks, the zone may extend to a depth of half the crater diameter or more (Dence et al. 1977, 263). The impact of a meteorite causing a crater larger than 0.6 mile (1 kilometer) in diameter could thus fracture the Salado above the repository.

Geological evidence for meteorite impacts on earth is rare because many meteorites fall into the oceans and erosion and sedimentation serve to obscure craters that form on land. Dietz (1961) estimated that meteorites that cause craters larger than 0.6 mile (1 kilometer) in diameter strike the earth at the rate of about one every 10,000 years (equivalent to about

2×10^{-13} impacts per square kilometer per year). Using observations from the Canadian Shield, Hartmann (1965, 161) estimated a frequency of between 0.8×10^{-13} and 17×10^{-13} per square kilometer per year for impacts causing craters larger than 0.6 mile (1 kilometer). Frequencies estimated for larger impacts in studies reported by Grieve (1987, 263) can be extrapolated to give a rate of about 1.3×10^{-12} per square kilometer per year for craters larger than 0.6 mile (1 kilometer). It is commonly assumed that meteorite impacts are randomly distributed across the earth's surface, although Halliday (1964, 267 – 277) calculated that the rate of impact in polar regions would be some 50 to 60 percent of that in equatorial regions. The frequencies reported by Grieve (1987) would correspond to an overall rate of about one per 1,000 years on the basis of a random distribution.

Assuming the higher estimated impact rate of 17×10^{-13} impacts per square kilometer per year for impacts leading to fracturing of sufficient extent to affect a deep repository and assuming a repository footprint of 0.9 mile × 1.0 mile (1.4 kilometers × 1.6 kilometers) for the WIPP yields a frequency of about 4×10^{-12} impacts per year for a direct hit above the repository. This impact frequency is several orders of magnitude below the screening limit of 10^{-4} per 10,000 years provided in 40 CFR § 194.32(d).

Meteorite hits directly above the repository footprint are not the only impacts of concern, however, because large craters may disrupt the waste panels even if the center of the crater is outside the repository area. It is possible to calculate the frequency of meteorite impacts that could disrupt a deep repository such as the WIPP by using the conservative model of a cylinder of rock fractured to a depth equal to one-half the crater diameter, as shown in Figure SCR-1. The area within which a meteorite could impact the repository is calculated by

$$S_D = (L + 2\times\frac{D}{2}) \times (W + 2\times\frac{D}{2}) ,$$

where

L = length of the repository footprint (kilometers)
W = width of the repository footprint (kilometers)
D = diameter of the impact crater (kilometers)
S_D = area of the region where the crater would disrupt the repository (square kilometers).

There are insufficient data on meteorites that have struck the earth to derive a distribution function for the size of craters directly. Using meteorite impacts on the moon as an analogy, however, Grieve (1987, 257) derived the following distribution function:

$$F_D \propto D^{-1.8} ,$$

where

F_D = frequency of impacts resulting in craters larger than D (impacts per square kilometer per year).

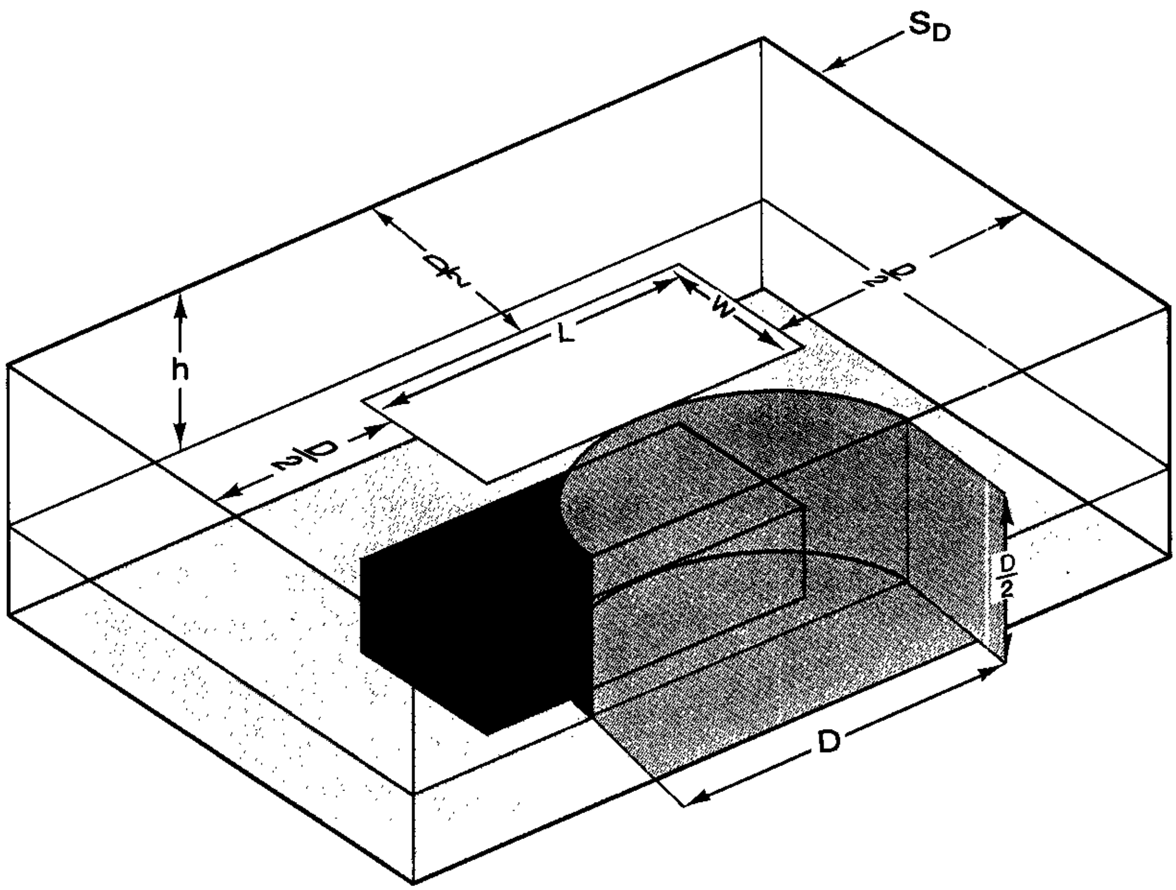

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Figure SCR-1. The Critical Region for Meteorite Impacts That Could Result in Fracturing of the Repository Horizon

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If f(D) denotes the frequency of impacts giving craters of diameter D, then the frequency of impacts giving craters larger than D is

$$F_D = \int_D^{\infty} f(D)dD$$

and

$$f(D) = F_1 \times 1.8 \times D^{-2.8} ,$$

where

- F_1 = frequency of impacts resulting in craters larger than 1 kilometer (impacts per square kilometer per year)
- f(D) = frequency of impacts resulting in craters of diameter D (impacts per square kilometer per year).

The overall frequency of meteorite impacts that could disrupt or fracture the repository is thus given by

$$N = \int_{2h}^{\infty} f(D) \times S_D \, dD ,$$

where

- h = depth to repository (kilometers)
- N = frequency of impacts leading to disruption of the repository (impacts per year)

$$N = 1.8F_1[1.8LW(2h)^{-1.8} + 0.8(L+W)(2h)^{-0.8} - 0.2(2h)^{0.2}] .$$

If it is assumed that the repository is located at a depth of 650 meters and has a footprint area of 0.9 mile × 1.0 mile (1.4 kilometers × 1.6 kilometers) and that meteorites creating craters larger than 1 kilometer in diameter hit the earth at a frequency (F_1) of 17×10^{-13} impacts per square kilometer per year, then the above equation gives a frequency of approximately 1.3×10^{-11} impacts per year for impacts disrupting the repository. If impacts are randomly distributed over time, this corresponds to a probability of 1.3×10^{-7} over 10,000 years.

Similar calculations have been performed that indicate rates of impact of between 10^{-12} and 10^{-13} per year for meteorites large enough to disrupt a deep repository (see, for example, Hartmann 1979, Kärnbränslesakerhet 1978, Claiborne and Gera 1974, Cranwell et al. 1990, and Thorne 1992). Meteorite impact can thus be eliminated from performance assessment calculations on the basis of low probability of occurrence over 10,000 years.

Assuming a random or nearly random distribution of meteorite impacts, cratering at any location is inevitable given sufficient time. Although repository depth and host-rock lithology may reduce the consequences of a meteorite impact, there are no repository locations or engineered systems that can reduce the probability of impact over 10,000 years.

SCR.1.4.3 Denudation

SCR.1.4.3.1 Weathering

The effects of chemical and mechanical weathering have been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system.

Mechanical weathering and **chemical weathering** are assumed to be occurring at or near the surface around the WIPP site, through processes such as exfoliation and leaching. The extent of these processes is limited and they will contribute little to the overall rate of erosion in the area or to the availability of material for other erosional processes. The effects of chemical and mechanical weathering have been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system.

SCR.1.4.3.2 Erosion

The effects of fluvial and aeolian erosion and mass wasting in the region of the WIPP have been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system.

The geomorphological regime on the Mescalero Plain (Los Medaños) in the region of the WIPP is dominated by aeolian processes. Dunes are present in the area, and although some are stabilized by vegetation, **aeolian erosion** will occur as they migrate across the area. Old dunes will be replaced by new dunes, and no significant changes in the overall thickness of aeolian material are likely to occur.

Currently, precipitation in the region of the WIPP is too low (about 13 inches [33 centimeters] per year) to cause perennial streams, and the relief in the area is too low for extensive sheet flood erosion during storms. An increase in precipitation to around 24 inches (61 centimeters) per year in cooler climatic conditions could result in perennial streams, but the nature of the relief and the presence of dissolution hollows and sinks will ensure that these streams remain small. Significant **fluvial erosion** is not expected during the next 10,000 years.

Mass wasting (the downslope movement of material caused by the direct effect of gravity) is important only in terms of sediment erosion in regions of steep slopes. In the vicinity of the WIPP, mass wasting will be insignificant under the climatic conditions expected over the next 10,000 years.

Erosion from wind, water, and mass wasting will continue in the WIPP region throughout the next 10,000 years at rates similar to those occurring at present. These rates are too low to affect the performance of the disposal system significantly. Thus, the effects of fluvial and aeolian erosion and mass wasting have been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system.

SCR.1.4.3.3 Sedimentation

The effects of aeolian, fluvial, and lacustrine deposition and sedimentation in the region of the WIPP have been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system.

The geomorphological regime on the Mescalero Plain (Los Medaños) in the region of the WIPP is dominated by aeolian processes, but although some dunes are stabilized by vegetation, no significant changes in the overall thickness of aeolian material are expected to occur. Vegetational changes during periods of wetter climate may further stabilize the dune fields, but **aeolian deposition** is not expected to significantly increase the overall thickness of the superficial deposits.

The limited extent of water courses in the region of the WIPP, under both present-day conditions and under the expected climatic conditions, will restrict the amount of **fluvial deposition** and **lacustrine deposition** in the region.

Mass wasting may be significant if it results in dams or modifies streams. In the region around the WIPP, the Pecos River forms a significant water course some 12 miles (19 kilometers) away, but the broadness of its valley precludes either significant mass wasting or the formation of large impoundments.

Sedimentation from wind, water, and mass wasting is expected to continue in the WIPP region throughout the next 10,000 years at the low rates similar to those occurring at present. These rates are too low to significantly affect the performance of the disposal system. Thus, the effects of aeolian, fluvial, and lacustrine deposition and sedimentation resulting from mass wasting have been eliminated from performance assessment calculations on the basis of low consequence.

SCR.1.4.4 Soil Development

Soil development has been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system.

The Mescalero caliche is a well-developed calcareous remnant of an extensive soil profile across the WIPP site and adjacent areas. Although this unit may be up to 10 feet (3 meters) thick, it is not continuous and does not prevent infiltration to the underlying formations. At Nash Draw, this caliche, dated in Lappin et al. (1989, 2-4) at 410,000 to 510,000 years old, is present in collapse blocks, indicating some growth of Nash Draw in the late Pleistocene. Localized gypsite spring deposits about 25,000 years old occur along the eastern flank of Nash Draw, but the springs are not currently active. The Berino soil, interpreted as 333,000 years old (Rosholt and McKinney 1980, Table 5), is a thin soil horizon above the Mescalero caliche. The persistence of these soils on the Livingston Ridge and the lack of deformation indicates the relative stability of the WIPP region over the past half-million years.

Continued growth of caliche may occur in the future but will be of low consequence in terms of its effect on infiltration. Other soils in the area are not extensive enough to affect the amount of infiltration that reaches underlying aquifers. **Soil development** has been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system.

SCR.1.5 Surface Hydrological FEPs

SCR.1.5.1 Fluvial

Stream and river flow has been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system.

No perennial streams are present at the WIPP site, and there is no evidence in the literature indicating that such features existed at this location since the Pleistocene (see, for example, Powers et al. 1978; and Bachman 1974, 1981, and 1987). The Pecos River is approximately 12 miles (19 kilometers) from the WIPP site and more than 300 feet (90 meters) lower in elevation. **Stream and river flow** have been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system.

SCR.1.5.2 Lacustrine

The effects of surface water bodies have been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system.

No standing **surface water bodies** are present at the WIPP site, and there is no evidence in the literature indicating that such features existed at this location during or after the Pleistocene (see, for example, Powers et al. 1978; and Bachman 1974, 1981, and 1987). In Nash Draw, lakes and spoil ponds associated with potash mines are located at elevations 100 feet (30 meters) below the elevation of the land surface at the location of the waste panels. There is no evidence in the literature to suggest that Nash Draw was formed by stream erosion or was at any time the location of a deep body of standing water, although shallow playa lakes have existed there at various times. Based on these factors, the formation of large lakes is unlikely and the formation of smaller lakes and ponds is of little consequence to the performance of the disposal system. The effects of surface water bodies have therefore been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system.

SCR.1.5.3 Groundwater Recharge and Discharge

Groundwater recharge, infiltration, and groundwater discharge are accounted for in performance assessment calculations.

The groundwater basin described in Section 2.2.1.4 is governed by flow from areas where the water table is high to areas where the water table is low. The height of the water table is governed by the amount of **groundwater recharge** reaching the water table, which in turn is a function of the vertical hydraulic conductivity and the partitioning of precipitation between evapotranspiration, runoff, and **infiltration**. Flow within the Rustler is also governed by the amount of **groundwater discharge** that takes place from the basin. In the region around the WIPP, the principal discharge areas are along Nash Draw and the Pecos River. Groundwater flow modeling accounts for infiltration, recharge, and discharge (Sections 2.2.1.4 and 6.4.10.2).

SCR.1.5.4 Changes in Surface Hydrology

Changes in groundwater recharge and discharge arising as a result of climate change are accounted for in performance assessment calculations. The effects of river flooding and lake formation have been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system.

Changes in recharge may affect groundwater flow and radionuclide transport in units such as the Culebra and Magenta dolomites. Changes in the surface environment driven by natural climate change are expected to occur over the next 10,000 years (see Section SCR.1.6.2). Groundwater basin modeling (Section 2.2.1.4) indicates that a change in recharge will affect the height of the water table in the area of the WIPP, and that this will in turn affect the direction and rate of groundwater flow.

The present-day water table in the vicinity of the WIPP is within the Dewey Lake at about 3,215 feet (980 meters) above mean sea level (Section 2.2.1.4.2.1). An increase in recharge relative to present-day conditions would raise the water table, potentially as far as the ground surface locally. Similarly, a decrease in recharge could result in a lowering of the water table. The low transmissivity of the Dewey Lake and the Rustler ensures that any such lowering of the water table will be at a slow rate, and lateral discharge from the groundwater basin is expected to persist for several thousand years after any decrease in recharge. Under the anticipated changes in climate over the next 10,000 years, the water table will not fall below the base of the Dewey Lake, and dewatering of the Culebra is not expected to occur during this period (Section 2.2.1.4).

Changes in groundwater recharge and discharge are accounted for in performance assessment calculations through definition of the boundary conditions for flow and transport in the Culebra (Section 6.4.9).

Intermittent flooding of stream channels and the formation of shallow lakes will occur in the WIPP region over the next 10,000 years. These may have a short-lived and local effect on the height of the water table, but are unlikely to affect groundwater flow in the Culebra.

Future occurrences of playa lakes or other longer-term floods will be remote from the WIPP and will have little consequence on system performance in terms of groundwater flow at the site. There is no reason to believe that any impoundments or lakes could form over the WIPP site itself. Thus, **river flooding** and **lake formation** have been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system.

SCR.1.6 Climatic FEPs

This section discusses climate change and glaciation in the WIPP region.

SCR.1.6.1 Climate

Precipitation and temperature are accounted for in performance assessment calculations.

The climate and meteorology of the region around the WIPP are described in Section 2.5.2. Precipitation in the region is low (about 13 inches [33 centimeters] per year) and temperatures are moderate with a mean annual temperature of about 63°F (17°C). **Precipitation** and **temperature** are important controls on the amount of recharge that reaches the groundwater system and are accounted for in performance assessment calculations by use of a sampled parameter for scaling flow velocity in the Culebra (Section 6.4.9 and Appendix PAR, Parameter 48).

SCR.1.6.2 Climate Change

SCR.1.6.2.1 Meteorological

Climate change is accounted for in performance assessment calculations.

Climate changes are instigated by changes in the earth's orbit, which affect the amount of insolation, and by feedback mechanisms within the atmosphere and hydrosphere. Models of these mechanisms, combined with interpretations of the geological record, suggest that the climate will become cooler and wetter in the WIPP region during the next 10,000 years as a result of natural causes. Other changes, such as fluctuations in radiation intensity from the sun and variability within the many feedback mechanisms, will modify this climatic response to orbital changes. The available evidence suggests that these changes will be less extreme than those arising from orbital fluctuations.

The effect of a change to cooler and wetter conditions is considered to be an increase in the amount of recharge, which in turn will affect the height of the water table (see Section SCR.1.5.4). The height of the water table across the groundwater basin is an important control on the rate and direction of groundwater flow within the Culebra (see Section 2.2.1.4), and hence potentially on transport of radionuclides released to the Culebra through the shafts or intrusion boreholes. Climate change is accounted for in performance assessment calculations through a sampled parameter used to scale groundwater flow velocity in the Culebra (Section 6.4.9 and Appendix PAR, Parameter 48).

SCR.1.6.2.2 Glaciation

Glaciation and the effects of permafrost have been eliminated from performance assessment calculations on the basis of low probability of occurrence over 10,000 years.

No evidence exists to suggest that the northern part of the Delaware Basin has been covered by continental glaciers at any time since the beginning of the Paleozoic Era. During the maximum extent of continental **glaciation** in the Pleistocene Epoch, glaciers extended into northeastern Kansas at their closest approach to southeastern New Mexico. There is no evidence that alpine glaciers formed in the region of the WIPP during the Pleistocene glacial periods.

According to the theory that relates the periodicity of climate change to perturbations in the earth's orbit, a return to a full glacial cycle within the next 10,000 years is highly unlikely (Imbrie and Imbrie 1980, 951).

Thus, glaciation has been eliminated from performance assessment calculations on the basis of low probability of occurrence over the next 10,000 years. Similarly, a number of processes associated with the proximity of an ice sheet or valley glacier, such as **permafrost** and accelerated slope erosion (solifluction) have been eliminated from performance assessment calculations on the basis of low probability of occurrence over the next 10,000 years.

SCR.1.7 Marine FEPs

SCR.1.7.1 Seas

The effects of estuaries, seas, and oceans have has been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system.

The WIPP site is more than 480 miles (800 kilometers) from the Pacific Ocean and from the Gulf of Mexico. **Estuaries** and **seas and oceans** have therefore been eliminated from performance assessment calculations on the basis of low consequence to the disposal system.

SCR.1.7.2 Marine Sedimentology

The effects of coastal erosion, and marine sediment transport and deposition have been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system.

The WIPP site is more than 480 miles (800 kilometers) from the Pacific Ocean and Gulf of Mexico. The effects of **coastal erosion** and **marine sediment transport and deposition** have therefore been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system.

SCR.1.7.3 Sea Level Changes

The effects of both short-term and long-term sea level changes have been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system.

The WIPP site is some 3,330 feet (1,015 meters) above sea level. Global **sea level change** may result in sea levels as much as 460 feet (140 meters) below that of the present day during glacial periods, according to Chappell and Shackleton (1986, 138). This can have marked effects on coastal aquifers. During the next 10,000 years, the global sea level can be expected to drop towards this glacial minimum, but this will not affect the groundwater system in the vicinity of the WIPP. Short-term changes in sea level, brought about by events such as meteorite impact, tsunamis, seiches, and hurricanes may raise water levels by several tens of meters. Such events have a maximum duration of a few days and will have no effect on the surface or groundwater systems at the WIPP site. Anthropogenic-induced global warming has been conjectured by Warrick and Oerlemans (1990, 278) to result in longer-term sea level rise. The magnitude of this rise, however, is not expected to be more than a few meters, and such a variation will have no effect on the groundwater system in the WIPP region. Thus, the effects of both short-term and long-term sea level changes have been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system.

SCR.1.8 Ecological FEPs

SCR.1.8.1 Flora and Fauna

The effects of the natural plants, animals, and microbes (flora and fauna) in the region of the WIPP have been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system.

The terrestrial and aquatic ecology of the region around the WIPP is described in Section 2.4.1. The **plants** in the region are predominantly shrubs and grasses. The most conspicuous **animals** in the area are jackrabbits and cottontails. **Microbes** are presumed to be present within the thin soil horizons. The effects of this flora and fauna in the region have been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system.

SCR.1.8.2 Changes in Flora and Fauna

The effects of natural ecological development likely to occur in the region of the WIPP have been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system.

The region around the WIPP is sparsely vegetated as a result of the climate and poor soil quality. Wetter periods are expected during the regulatory period, but botanical records indicate that, even under these conditions, dense vegetation will not be present in the region (Swift 1992; see Appendix CLI, 17). The effects of the indigenous fauna are of low consequence to the performance of the disposal system and no natural events or processes have been identified that would lead to a change in this fauna that would be of consequence to system performance. **Natural ecological development** in the region of the WIPP has therefore been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system.

SCR.2 Waste- and Repository-Induced FEPs

In Section SCR.2, the DOE discusses waste- and repository-induced FEPs in the context of the FEP categorization scheme presented in Table SCR-2. Waste- and repository-induced FEPs are potentially relevant to the analyses conducted to evaluate compliance with 40 CFR § 191.13, 40 CFR § 191.15, and 40 CFR § 191.24. Note that the categories concerned with geology and mechanics (SCR.2.3), hydrology and fluid dynamics (SCR.2.4). and geochemistry and chemistry (SCR.2.5) relate to structure, fluid flow, and fluid chemistry, respectively, within the repository and the rest of the disposal system. The categories concerned with contaminant transport modes (SCR.2.6) and processes (SCR.2.7), and ecology (SCR.2.8) relate to the potential migration of radionuclides through the disposal system to the accessible environment. FEPs presented in Table SCR-2 are printed in bold in the text of the FEP screening discussions.

SCR.2.1 Waste and Repository Characteristics

SCR.2.1.1 Repository Characteristics

The WIPP repository disposal geometry is accounted for in performance assessment calculations.

Disposal geometry is described in Chapter 3.0 and is accounted for in the setup of performance assessment calculations (Section 6.4.3).

SCR.2.1.2 Waste Characteristics

The waste inventory and heterogeneity of the waste forms are accounted for in performance assessment calculations.

Table SCR-2. Waste- and Repository-Induced FEPs and Their Screening Classifications

Features, Events, and Processes (FEPs)	Screening Classification	Comments	Appendix SCR Section
WASTE AND REPOSITORY CHARACTERISTICS			SCR.2.1
Repository characteristics			SCR.2.1.1
Disposal geometry	UP		
Waste characteristics			SCR.2.1.2
Waste inventory	UP		
Heterogeneity of waste forms	DP		
Container characteristics			SCR.2.1.3
Container form	SO-C		
Container material inventory	UP		
Seal characteristics			SCR.2.1.4
Seal geometry	UP		
Seal physical properties	UP		
Seal chemical composition	SO-C	Beneficial SO-C	
Backfill characteristics			SCR.2.1.5
Backfill physical properties	SO-C		
Backfill chemical composition	UP		
Postclosure monitoring			SCR.2.1.6
Postclosure monitoring	SO-C		
RADIOLOGICAL FEPS			SCR.2.2
Radioactive decay			SCR.2.2.1
Radionuclide decay and ingrowth	UP		
Heat from radioactive decay			SCR.2.2.2
Heat from radioactive decay	SO-C		
Nuclear criticality			SCR.2.2.3
Nuclear criticality: heat	SO-P		
Radiological effects on material properties			SCR.2.2.4
Radiological effects on waste	SO-C		
Radiological effects on containers	SO-C		
Radiological effects on seals	SO-C		
GEOLOGICAL AND MECHANICAL FEPS			SCR.2.3
Excavation-induced fracturing			SCR.2.3.1
Disturbed rock zone	UP		
Excavation-induced changes in stress	UP		
Rock creep			SCR.2.3.2
Salt creep	UP		
Changes in the stress field	UP		
Roof falls			SCR.2.3.3
Roof falls	UP		
Subsidence			SCR.2.3.4
Subsidence	SO-C		
Large scale rock fracturing	SO-P		

Table SCR-2. Waste- and Repository-Induced FEPs and Their Screening Classifications (Continued)

Features, Events, and Processes (FEPs)	Screening Classification	Comments	Appendix SCR Section
Effects of fluid pressure changes			SCR.2.3.5
Disruption due to gas effects	UP		
Pressurization	UP		
Effects of explosions			SCR.2.3.6
Gas explosions	UP		
Nuclear explosions	SO-P		
Thermal effects			SCR.2.3.7
Thermal effects on material properties	SO-C		
Thermally-induced stress changes	SO-C		
Differing thermal expansion of repository components	SO-C		
Mechanical effects on material properties			SCR.2.3.8
Consolidation of waste	UP		
Movement of containers	SO-C		
Container integrity	SO-C	Beneficial SO-C	
Mechanical effects of backfill	SO-C		
Consolidation of seals	UP		
Mechanical degradation of seals	UP		
Investigation boreholes	SO-C		
Underground boreholes	UP		
SUBSURFACE HYDROLOGICAL AND FLUID DYNAMICAL FEPS			SCR.2.4
Repository-induced flow			SCR.2.4.1
Brine inflow	UP		
Wicking	UP		
Effects of gas generation			SCR.2.4.2
Fluid flow due to gas production	UP		
Thermal effects			SCR.2.4.3
Convection	SO-C		
GEOCHEMICAL AND CHEMICAL FEPS			SCR.2.5
Gas generation			SCR.2.5.1
Microbial gas generation			SCR.2.5.1.1
Degradation of organic material	UP		
Effects of temperature on microbial gas generation	UP		
Effects of pressure on microbial gas generation	SO-C		
Effects of radiation on microbial gas generation	SO-C		
Effects of biofilms on microbial gas generation	UP		

Table SCR-2. Waste- and Repository-Induced FEPs and Their Screening Classifications (Continued)

Features, Events, and Processes (FEPs)	Screening Classification	Comments	Appendix SCR Section
Corrosion			SCR.2.5.1.2
Gases from metal corrosion	UP		
Galvanic coupling	SO-P		
Chemical effects of corrosion	UP		
Radiolytic gas generation			SCR.2.5.1.3
Radiolysis of brine	SO-C		
Radiolysis of cellulose	SO-C		
Helium gas production	SO-C		
Radioactive gases	SO-C		
Chemical speciation			SCR.2.5.2
Speciation	UP	UP in disposal rooms and Culebra. SO-C elsewhere, and beneficial SO-C in cementitious seals.	
Kinetics of speciation	SO-C		
Precipitation and dissolution			SCR.2.5.3
Dissolution of waste	UP		
Precipitation	SO-C	Beneficial SO-C	
Kinetics of precipitation and dissolution	SO-C	Kinetics of waste dissolution is a beneficial SO-C	
Sorption			SCR.2.5.4
Actinide sorption	UP	UP in the Culebra and Dewey Lake. Beneficial SO-C elsewhere	
Kinetics of sorption	UP		
Changes in sorptive surfaces	UP		
Reduction-oxidation chemistry			SCR.2.5.5
Effect of metal corrosion	UP		
Reduction-oxidation fronts	SO-P		
Reduction-oxidation kinetics	UP		
Localized reducing zones	SO-C		
Organic complexation			SCR.2.5.6
Organic complexation	SO-C		
Organic ligands	SO-C		
Humic and fulvic acids	UP		
Kinetics of organic complexation	SO-C		
Exothermic reactions			SCR.2.5.7
Exothermic reactions	SO-C		
Concrete hydration	SO-C		
Chemical effects on material properties			SCR.2.5.8
Chemical degradation of seals	UP		
Chemical degradation of backfill	SO-C		

Table SCR-2. Waste- and Repository-Induced FEPs and Their Screening Classifications (Continued)

Features, Events, and Processes (FEPs)	Screening Classification	Comments	Appendix SCR Section
Microbial growth on concrete	UP		
CONTAMINANT TRANSPORT MODE FEPS			SCR.2.6
Solute transport			SCR.2.6.1
Solute transport	UP		
Colloid transport			SCR.2.6.2
Colloid transport	UP		
Colloid formation and stability	UP		
Colloid filtration	UP		
Colloid sorption	UP		
Particulate transport			SCR.2.6.3
Suspensions of particles	DP	SO-C for undisturbed conditions	
Rinse	SO-C		
Cuttings	DP	Repository intrusion only	
Cavings	DP	Repository intrusion only	
Spallings	DP	Repository intrusion only	
Microbial transport			SCR.2.6.4
Microbial transport	UP		
Biofilms	SO-C	Beneficial SO-C	
Gas transport			SCR.2.6.5
Transport of radioactive gases	SO-C		
CONTAMINANT TRANSPORT PROCESSES			SCR.2.7
Advection			SCR.2.7.1
Advection	UP		
Diffusion			SCR.2.7.2
Diffusion	UP		
Matrix diffusion	UP		
Thermochemical transport phenomena			SCR.2.7.3
Soret effect	SO-C		
Electrochemical transport phenomena			SCR.2.7.4
Electrochemical effects	SO-C		
Galvanic coupling	SO-P		
Electrophoresis	SO-C		
Physicochemical transport phenomena			SCR.2.7.5
Chemical gradients	SO-C		
Osmotic processes	SO-C	Beneficial SO-C	
Alpha recoil	SO-C		
Enhanced diffusion	SO-C		

Table SCR-2. Waste- and Repository-Induced FEPs and Their Screening Classifications (Continued)

Features, Events, and Processes (FEPs)	Screening Classification	Comments	Appendix SCR Section
ECOLOGICAL FEPS			SCR.2.8
Plant, animal, and soil uptake			SCR.2.8.1
Plant uptake	SO-R	SO-C for 40 CFR § 191.15	
Animal uptake	SO-R		
Accumulation in soils	SO-C	Beneficial SO-C	
Human uptake			SCR.2.8.2
Ingestion	SO-R	SO-C for 40 CFR § 191.15	
Inhalation	SO-R	SO-C for 40 CFR § 191.15	
Irradiation	SO-R	SO-C for 40 CFR § 191.15	
Dermal sorption	SO-R	SO-C for 40 CFR § 191.15	
Injection	SO-R	SO-C for 40 CFR § 191.15	

Legend:

- UP — FEPs accounted for in the assessment calculations for undisturbed performance for 40 CFR § 191.13 (as well as 40 CFR § 191.15 and Subpart C of 40 CFR Part 191).
- DP — FEPs accounted for (in addition to all UP FEPs) in the assessment calculations for disturbed performance for 40 CFR § 191.13.
- SO-R — FEPs eliminated from performance assessment calculations on the basis of regulations provided in 40 CFR Part 191 and criteria provided in 40 CFR Part 194.
- SO-C — FEPs eliminated from performance assessment (and compliance assessment) calculations on the basis of consequence.
- SO-P — FEPs eliminated from performance assessment (and compliance assessment) calculations on the basis of low probability of occurrence.

Waste characteristics, comprising the **waste inventory** and the **heterogeneity of waste forms,** are described in Chapter 4.0. The waste inventory is accounted for in performance assessment calculations in deriving the dissolved actinide source term and gas generation rates (Sections 6.4.3.5 and 6.4.3.3). The distribution of contact-handled (CH) and remote-handled (RH) transuranic (TRU) waste within the repository leads to room scale heterogeneity of the waste forms, which is accounted for in performance assessment calculations when considering the potential activity of waste material encountered during inadvertent borehole intrusion (Section 6.4.7).

SCR.2.1.3 Container Characteristics

The container material inventory is accounted for in performance assessment calculations. The container form has been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system.

The **container material inventory** is described in Chapter 4.0, and is accounted for in performance assessment calculations through the estimation of gas generation rates (Section 6.4.3.3). **Container form** will affect container strength through the shape and dimensions of the container and affect heat dissipation through container volume and surface area. Long-term container performance has been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system (Section SCR.2.3.8). Heat generation from the waste is also considered of low consequence to the performance of the disposal system (Section SCR.2.2.2). Container form has, therefore, been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system.

SCR.2.1.4 Seal Characteristics

The seal geometry and seal physical properties are accounted for in performance assessment calculations. The seal chemical composition has been eliminated from performance assessment calculations on the basis of beneficial consequence to the performance of the disposal system.

Seal (shaft seals, panel closures, and drift closures) characteristics, including **seal geometry** and **seal physical properties**, are described in Chapter 3.0 and are accounted for in performance assessment calculations through the representation of the seal system in BRAGFLO and the permeabilities assigned to the seal materials (Section 6.4.4). The effect of shaft **seal chemical composition** on actinide speciation and mobility is discussed in Section SCR.2.5.2 and has been eliminated from performance assessment calculations on the basis of beneficial consequence to the performance of the disposal system.

SCR.2.1.5 Backfill Characteristics

The backfill chemical composition is accounted for in performance assessment calculations. Backfill physical properties have been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system.

A chemical conditioner (hereafter referred to as backfill) will be added to the disposal room to buffer the chemical environment. The backfill characteristics are described in Section 6.4.3.4. The mechanical and thermal effects of backfill are discussed in Sections SCR.2.3.8.1 and SCR.2.5.7.2, respectively, where they have been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system. Backfill will result in an initial permeability for the disposal room lower than that of an empty cavity, so neglecting the hydrological effects of backfill is a conservative assumption with regard to brine inflow and radionuclide migration. Thus, **backfill physical properties** have been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system. The chemical effects of backfill are discussed in Section SCR.2.5.2.1 and the **backfill chemical composition** is accounted for in performance assessment calculations in deriving the dissolved and colloidal actinide source terms (Section 6.4.3).

SCR.2.1.6 Postclosure Monitoring

The potential effects of postclosure monitoring have been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system.

Postclosure monitoring is required by 40 CFR § 191.14(b) as an assurance requirement to "detect substantial and detrimental deviations from expected performance." The DOE has designed the monitoring program (see Appendix MON) so that the monitoring methods employed are not detrimental to the performance of the disposal system. Long-term monitoring would not be expected to lead to a need for remedial activities. In summary, the effects of monitoring have been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system.

SCR.2.2 Radiological FEPs

SCR.2.2.1 Radioactive Decay

Radioactive decay and ingrowth are accounted for in performance assessment calculations.

Radionuclide decay and ingrowth are accounted for in performance assessment calculations (see Section 6.4.12.4).

SCR.2.2.2 Heat from Radioactive Decay

The effects of temperature increases as a result of radioactive decay have been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system.

Radioactive decay of the waste emplaced in the repository will generate heat. The importance of **heat from radioactive decay** depends on the effects that the induced temperature changes would have on mechanics (Section SCR.2.3.7), fluid flow (Section SCR.2.4.3), and geochemical processes (Section SCR.2.5). For example, extreme temperature increases could result in thermally induced fracturing, regional uplift, or thermally driven flow of gas and brine in the vicinity of the repository.

According to the Waste Acceptance Criteria (WAC) (see Chapter 4.0), the design basis for the WIPP requires that the thermal loading does not exceed 10 kilowatts per acre. The WAC also require that the thermal power generated by waste in an RH-TRU container shall not exceed 300 watts, but the WAC do not limit the thermal power of CH-TRU waste containers.

A numerical study to calculate induced temperature distributions and regional uplift is reported in DOE (1980, 9-149 to 9-150). This study involved estimation of the thermal power of CH-TRU waste containers. The DOE (1980, 9-149) analysis assumed the following:

- All CH-TRU waste drums and boxes contain the maximum permissible quantity of plutonium. According to the WAC, the fissionable radionuclide content for CH-TRU waste containers shall be no greater than 200 grams per 0.21 cubic meter drum and 350 grams per 1.8 cubic meter standard waste box (^{239}Pu fissile gram equivalents).

- The plutonium in CH-TRU waste containers is weapons grade material producing heat at 0.0024 watts per gram. Thus, the thermal power of a drum is approximately 0.5 watts and that of a box is approximately 0.8 watts.

- Approximately 3.7×10^5 cubic meters of CH-TRU waste are distributed within a repository enclosing an area of 7.3×10^5 square meters. This is a conservative assumption in terms of quantity and density of waste within the repository, because the maximum capacity of the WIPP is 1.756×10^5 cubic meters for all waste (as specified by the Land Withdrawal Act [LWA]) to be placed in an enclosed area of approximately 5.1×10^5 square meters.

- Half of the CH-TRU waste volume is placed in drums and half in boxes so that the repository will contain approximately 9×10^5 drums and 10^5 boxes. Thus, a calculated thermal power of 2.8 kilowatts per acre (0.7 watts per square meter) of heat is generated by the CH-TRU waste.

- Insufficient RH-TRU waste is emplaced in the repository to influence the total thermal load.

Under these assumptions, Thorne and Rudeen (1981) estimated the long-term temperature response of the disposal system to waste emplacement. Calculations assumed a uniform initial power density of 2.8 kilowatts per acre (0.7 watts per square meter) which decreases over time. Thorne and Rudeen (1981) attributed this thermal load to RH-TRU waste, but the DOE (1980), more appropriately, attributed this thermal load to CH-TRU waste based on the assumptions listed above. Thorne and Rudeen (1981) estimated the maximum rise in temperature at the center of a repository to be 1.6°C at 80 years after waste emplacement.

Sanchez and Trellue (1996) estimated the maximum thermal power of an RH-TRU waste container. The Sanchez and Trellue (1996) analysis involved inverse shielding calculations to evaluate the thermal power of an RH-TRU container corresponding to the maximum permissible surface dose; according to the WAC, the maximum allowable surface dose equivalent for RH-TRU containers is 1000 rem per hour. The following calculational steps were taken in the Sanchez and Trellue (1996) analysis:

- Calculate the absorbed dose rate for gamma radiation corresponding to the maximum surface dose equivalent rate of 1000 rem per hour. Beta and alpha radiation are not included in this calculation because such particles will not penetrate the waste matrix or the container in significant quantities. Neutrons are not included in the analysis because, according to the WAC, the maximum dose rate from neutrons is 270 millirem per hour, and the corresponding neutron heating rate will be insignificant.

- Calculate the exposure rate for gamma radiation corresponding to the absorbed dose rate for gamma radiation.

- Calculate the gamma flux density at the surface of a RH-TRU container corresponding to the exposure rate for gamma radiation. Assuming the gamma energy is 1.0 megaelectron volts, the maximum allowable gamma flux density at the surface of a RH-TRU container is about 5.8×10^8 gamma rays per square centimeter per second.

- Determine the distributed gamma source strength, or gamma activity, in an RH-TRU container from the surface gamma flux density. The source is assumed to be shielded such that the gamma flux is attenuated by the container and by absorbing material in the container. The level of shielding depends on the matrix density. Scattering of the gamma flux, with loss of energy, is also accounted for in this calculation through inclusion of a gamma buildup factor. The distributed gamma source strength is determined assuming a uniform source in a right cylindrical container. The maximum total gamma source (gamma curies) is then calculated for a RH-TRU container containing 0.89 cubic meters of waste. For the waste of greatest expected density (about 6,000 kilograms per cubic meter), the gamma source is about 2×10^4 curies per cubic meter.

- Calculate the total curie load of a RH-TRU container (including alpha and beta radiation) from the gamma load. The ratio of the total curie load to the gamma curie load was estimated through examination of the radionuclide inventory presented in Appendix BIR. The gamma curie load and the total curie load for each radionuclide listed in the WIPP BIR were summed. Based on these summed loads the ratio of total curie load to gamma curie load of RH-TRU waste was calculated to be 1.01.

- Calculate the thermal load of a RH-TRU container from the total curie load. The ratio of thermal load to curie load was estimated through examination of the radionuclide inventory presented in Appendix BIR. The thermal load and the total curie load for each radionuclide listed in the WIPP BIR were summed. Based on these summed loads the ratio of thermal load to curie load of RH-TRU waste was calculated to be about 0.0037 watts per curie. For a gamma source of 2×10^4 curies per cubic meter, the maximum permissible thermal load of a RH-TRU container is about 70 watts per cubic meter. Thus, the maximum thermal load of a RH-TRU container is about 60 watts, and the WAC upper limit of 300 watts will not be achieved.

Note that Sanchez and Trellue (1996) calculated the average thermal load for a RH-TRU container to be less than 1 watt. Also, the total RH-TRU heat load is less than 10 percent of the total heat load in the WIPP. Thus, the total thermal load of the RH-TRU waste will not significantly affect the average rise in temperature in the repository resulting from decay of CH-TRU waste.

Temperature increases will be greater at locations where the thermal power of an RH-TRU container is 60 watts, if any such containers are emplaced. Sanchez and Trellue (1996) estimated the temperature increase at the surface of a 60 watt RH-TRU waste container. Their analysis involved solution of a steady-state thermal conduction problem with a constant heat source term of 70 watts per cubic meter. These conditions represent conservative assumptions because the thermal load will decrease with time as the radioactive waste decays. The temperature increase at the surface of the container was calculated to be about 3°C.

In summary, analysis has shown that the average temperature increase in the WIPP repository, due to radioactive decay of the emplaced CH- and RH-TRU waste, will be less than 2°C. Temperature increases of about 3°C may occur in the vicinity of RH-TRU containers with the highest allowable thermal load of about 60 watts (based on the maximum allowable surface dose equivalent for RH-TRU containers). Potential heat generation from nuclear criticality is discussed in Section SCR.2.2.3 and exothermic reactions are discussed in Section SCR.2.5.7. The effects of repository temperature changes on mechanics (Section SCR.2.3.7), fluid flow (Section SCR.2.4.3), and geochemical processes (SCR.2.5) have been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system.

SCR.2.2.3 Nuclear Criticality

Nuclear criticality has been eliminated from performance assessment calculations on the basis of low probability of occurrence over 10,000 years.

Nuclear criticality refers to a sustained fission reaction that may occur if fissile radionuclides reach both a sufficiently high concentration and total mass (where the latter parameter includes the influence of enrichment of the fissile radionuclides). In the subsurface, the primary effect of a nuclear reaction is the production of **heat**.

The possibility of a nuclear criticality in the waste disposal region has been eliminated from performance assessment calculations because of the low initial concentration of the fissile radionuclides (that is, the WAC limits the fissile radionuclides in the CH- and RH-TRU containers) and because no credible mechanism exists to further concentrate the fissile radionuclides after closure. To elaborate, possible mechanisms for concentration in the waste disposal region include high solubility, compaction, sorption, and precipitation. First, the maximum solubility of ^{239}Pu in the WIPP repository, the most abundant fissile radionuclide, is orders of magnitude lower than necessary to create a critical solution. The same is true for ^{235}U, the other primary fissile radionuclide. Second, the waste is assumed to be compacted by repository processes to one fourth its original volume. This compaction is still an order of magnitude too disperse (many orders of magnitude too disperse if neutron absorbers that prevent criticality (for example, ^{238}U) are included). Third, any potential sorbents in the waste would be fairly uniformly distributed throughout the waste disposal region; consequently, concentration of fissile radionuclides in localized areas through sorption is improbable. Fourth, precipitation requires significant localized changes in brine chemistry; small local variations are insufficient to separate substantial amounts of ^{239}Pu from other actinides in the waste disposal region that can prevent a criticality (for example, 11 times more ^{238}U is present than ^{239}Pu).

The possibility of a criticality in the far field along the transport pathways to the accessible environment (primarily the Culebra and marker beds in the Salado) has been eliminated from performance assessment calculations because a geometry favorable for criticality will not be achieved by fissile radionuclides that may become immobile in the Culebra or marker beds. As discussed in Section 6.4.6.2 and Appendix MASS Section 15, the porosity in the dolomite consists of intergranular porosity, vugs, microscopic fractures, and macroscopic fractures. As discussed in Section 6.4.5.2, porosity in the marker beds consists of partially healed fractures that may dilate as pressure increases. Advective flow in both units occurs mostly through macroscopic fractures. Consequently, any potential deposition through precipitation or sorption is constrained by the depth to which precipitation and sorption occur away from fractures. This geometry is not favorable for fission reactions and eliminates the possibility of a criticality. Thus, nuclear criticality has been eliminated from performance assessment calculations on the basis of low probability of occurrence. The potential for nuclear criticality is discussed in more detail by Rechard et al. (1996). Potential heat generation from radioactive decay is discussed in Section SCR.2.2.2 and exothermic reactions are discussed in Section SCR.2.5.7.

SCR.2.2.4 Radiological Effects on Material Properties

Radiological effects on the properties of the waste, container, and seals, have been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system.

Ionizing radiation can change the physical properties of many materials. Strong radiation fields could lead to damage of waste matrices, brittleness of the metal containers, and disruption of any crystalline structure in the seals. However, the low level of activity of the waste in the WIPP is unlikely to generate a strong radiation field. In addition, performance assessment calculations assume instantaneous container failure and waste dissolution according to the source-term model (see Section 6.4.3.4, 6.4.3.5, and 6.4.3.6). Therefore, **radiological effects on the properties of** the **waste**, **containers**, and **seals**, have been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system.

SCR.2.3 Geological and Mechanical FEPs

SCR.2.3.1 Excavation-Induced Fracturing

Excavation-induced host rock fracturing through formation of a DRZ and changes in stress are accounted for in performance assessment calculations.

Construction of the repository has caused local **excavation-induced changes in stress** in the surrounding rock as discussed in Section 3.3.1.5. This has led to failure of intact rock around the opening, creating a **disturbed rock zone** of fractures. On completion of the WIPP excavation, the extent of the induced stress field perturbation will be sufficient to have caused dilation and fracturing in the anhydrite layers a and b, marker bed (MB) 139, and, possibly, MB138. The creation of the DRZ around the excavation and the disturbance of the anhydrite layers and marker beds will alter the permeability and effective porosity of the rock around the repository, providing enhanced pathways for flow of gas and brine between the waste-filled rooms and the nearby interbeds. This excavation-induced, host-rock fracturing is accounted for in performance assessment calculations (Section 6.4.5.3).

The DRZ around repository shafts could provide pathways for flow from the repository to hydraulically conductive units above the repository horizon. The effectiveness of long-term shaft seals is dependent upon the seals providing sufficient backstress for salt creep to heal the DRZ around them, so that connected flow paths out of the repository horizon will cease to exist. These factors are considered in the current seal design.

SCR.2.3.2 Rock Creep

Salt creep in the Salado and resultant changes in the stress field are accounted for in performance assessment calculations.

Salt creep will lead to **changes in the stress field**, compaction of the waste and containers, and consolidation of the long-term components of the sealing system. It will also tend to close fractures in the DRZ, leading to reductions in porosity and permeability, increases in pore fluid pressure, and reductions in fluid flow rates in the repository. Salt creep in the Salado is accounted for in performance assessment calculations (Section 6.4.3.1). The long-term repository seal system relies on the consolidation of the crushed-salt seal material and healing of the DRZ around the seals to achieve a low permeability under stresses induced by salt creep. Seal performance is discussed further in Section SCR.2.3.8.2.

SCR.2.3.3 Roof Falls

The potential effects of roof falls on flow paths are accounted for in performance assessment calculations.

Instability of the DRZ could to lead to localized **roof falls** in the first few hundred years. If instability of the DRZ causes roof falls, development of the DRZ may be sufficient to disrupt the anhydrite layers above the repository, which may create a zone of rock containing anhydrite extending from the interbeds toward a waste-filled room. Fracture development is most likely to be induced as the rock stress and strain distributions evolve because of creep. In the long term, the effects of roof falls in the repository are likely to be minor because salt creep will reduce the void space and the potential for roof falls as well as leading to healing of any roof material that has fallen into the rooms. However, because of uncertainty in the process by which the disposal room DRZ heals, the flow model used in the performance assessment assumes that a higher permeability zone remains for the long term. Thus, the potential effects of roof falls on flow paths are accounted for in performance assessment calculations through appropriate ranges of the parameters describing the DRZ.

SCR.2.3.4 Subsidence

Fracturing within units overlying the Salado and surface displacement caused by subsidence associated with repository closure has been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system. The potential for excavation or repository-induced subsidence to create large-scale rock fracturing and fluid flow paths between the repository and units overlying the Salado has been eliminated from performance assessment calculations on the basis of the low probability of occurrence over 10,000 years.

Subsidence through salt creep or roof collapse associated with excavation might affect the hydrologic properties of units above the repository and might cause **large-scale rock fracturing** between the repository horizon and the surface.

The amount of subsidence that can occur as a result of salt creep closure or roof collapse in the WIPP excavation depends primarily on the volume of excavated rock, the initial and compressed porosities of the various emplaced materials (waste, backfill, panel and drift closures, and seals), the amount of inward creep of the repository walls, and the gas and fluid pressures within the repository. The DOE (Westinghouse 1994) has analyzed potential excavation-induced subsidence with the primary objective of determining the geomechanical advantage of backfilling the WIPP excavation. The DOE (Westinghouse 1994, 3-4 to 3-23) used mass conservation calculations, the influence function method, the National Coal Board empirical method, and the two-dimensional, finite-difference code, Fast Lagrangian Analysis of Continua (FLAC) to estimate subsidence for conditions ranging from no backfill to emplacement of a highly compacted crushed salt backfill. The DOE (Westinghouse 1994, 2-17 to 2-23) also investigated subsidence at potash mines located near the WIPP site to gain insight into the expected subsidence conditions at the WIPP and to calibrate the subsidence calculation methods.

Subsidence over potash mines will be much greater than subsidence over the WIPP because of the significant differences in stratigraphic position, depth, extraction ratio, and layout. The WIPP site is located stratigraphically lower than the lowest potash mine, which is near the base of the McNutt Potash Member (hereafter called the McNutt). At the WIPP site, the base of the McNutt is about 490 feet (150 meters) above the repository horizon. Also, the WIPP rock extraction ratio in the waste disposal region will be about 22 percent, as compared to 65 percent for the lowest extraction ratios within potash mines investigated by the DOE (Westinghouse 1994, 2-17).

The DOE (Westinghouse 1994, 2-22) reported the maximum total subsidence at potash mines to be about 5 feet (1.5 meters). This level of subsidence has been observed to have caused surface fractures. However, the DOE (Westinghouse 1994, 2-23) found no evidence that subsidence over potash mines had caused fracturing sufficient to connect the mining horizon to water-bearing units or the landsurface. The level of disturbance caused by subsidence above the WIPP repository will be less than that associated with potash mining and thus, by analogy, will not create fluid flow paths between the repository and the overlying units.

The various subsidence calculation methods used by the DOE (Westinghouse 1994, 3-4 to 3-23) provided similar and consistent results, which support the premise that subsidence over the WIPP will be less than subsidence over potash mines. Estimates of maximum subsidence at the land surface for the cases of no backfill and highly compacted backfill are 2 feet (0.62 meters) and 1.7 feet (0.52 meters), respectively. The mass conservation method gave the upper bound estimate of subsidence in each case. The surface topography in the WIPP area varies by more than 10 feet (3 meters), so the expected amount of repository-induced subsidence will not create a basin, and will not affect surface hydrology significantly. The DOE (Westinghouse 1994, Table 3-13) also estimated subsidence at the depth of the Culebra using the FLAC model, for the case of an empty repository (containing no waste or backfill). The FLAC analysis assumed the Salado to be halite and the Culebra to have anhydrite material parameters.

Maximum subsidence at the Culebra was estimated to be 1.8 feet (0.56 meters). The vertical strain was concentrated in the Salado above the repository. Vertical strain was less than 0.01 percent in units overlying the Salado and was close to zero in the Culebra (Westinghouse 1994, Figure 3-40). The maximum horizontal displacement in the Culebra was estimated to be 0.08 feet (0.02 meters), with a maximum tensile horizontal strain of 0.007 percent. The DOE (Westinghouse 1994, 4-1 to 4-2) concluded that the induced strains in the Culebra will be uniformly distributed because no large-scale faults or discontinuities are present in the vicinity of the WIPP. Furthermore, strains of this magnitude would not be expected to cause extensive fracturing.

At the WIPP site, the Culebra hydraulic conductivity varies spatially over approximately four orders of magnitude, from 1×10^{-8} meters per second (0.4 meters per year) to 1×10^{-5} meters per second (400 meters per year) (Section 2.2.1.4.1.2). Where transmissive horizontal fractures exist, hydraulic conductivity in the Culebra is dominated by flow through the fractures. An induced tensile vertical strain may result in an increase in fracture aperture and corresponding increases in hydraulic conductivity. The magnitude of increase in hydraulic conductivity can be estimated by approximating the hydrological behavior of the Culebra with a simple conceptual model of fluid flow through a series of parallel fractures with uniform properties. A conservative estimate of the change in hydraulic conductivity can be made by assuming that all the vertical strain is translated to fracture opening (and none to rock expansion). This method for evaluating changes in hydraulic conductivity is similar to that used by the U.S. Environmental Protection Agency (EPA) in estimating the effects of subsidence caused by potash mining (Peake 1996, EPA 1996, 9-38 to 9-60).

The equivalent porous medium hydraulic conductivity, K (meters per second), of a system of parallel fractures can be calculated assuming the cubic law for fluid flow (Witherspoon et al. 1980):

$$K = \frac{w^3 \rho g N}{12 \mu D} ,$$

where w is the fracture aperture, ρ is the fluid density (taken to be 1,000 kilograms per cubic meter), g is the acceleration due to gravity (9.79 meters per second squared), μ is the fluid viscosity (taken as 0.001 pascal seconds), D is the effective Culebra thickness (7.7 meters), and N is the number of fractures.

For 10 fractures with a fracture aperture, w, of 6×10^{-5} meters, the Culebra hydraulic conductivity, K, is approximately 7 meters per year (2×10^{-7} meters per second). The values of the parameters used in this calculation are within the range of those expected for the Culebra at the WIPP site (Section 2.2.1.4.1.2).

The amount of opening of each fracture as a result of subsidence-induced tensile vertical strain, ϵ, (assuming rigid rock) is $D\epsilon/N$ meters. Thus, for a vertical strain of 0.0001 meters per meter, the fracture aperture, w, becomes approximately 1.4×10^{-4} meters. The Culebra hydraulic conductivity, K, then increases to approximately 85 meters per year (2.7×10^{-6} meters per second). Thus, on the basis of a conservative estimate of vertical strain, the hydraulic conductivity of the Culebra may increase by an order of magnitude. In the performance assessment calculations, multiple realizations of the Culebra transmissivity field are generated as a means of accounting for spatial variability and uncertainty (Appendix TFIELD). A change in hydraulic conductivity of one order of magnitude through vertical strain is within the range of uncertainty incorporated in the Culebra transmissivity field through these multiple realizations. Thus, changes in the horizontal component of Culebra hydraulic conductivity resulting from repository-induced subsidence have been eliminated from performance assessment calculations on the basis of low consequence.

A similar calculation can be performed to estimate the change in vertical hydraulic conductivity in the Culebra as a result of a horizontal strain of 0.00007 meters per meter (Westinghouse 1994, 3-20). Assuming this strain to be distributed over about 1,000 fractures (neglecting rock expansion), with zero initial aperture, in a lateral extent of the Culebra of about 800 meters (Westinghouse 1994, Figure 3-39), then the subsidence-induced fracture aperture is approximately 6×10^{-5} meters. Using the values for ρ, g, and μ, above, the vertical hydraulic conductivity of the Culebra can then be calculated, through an equation similar to above, to be 7 meters per year (2×10^{-7} meters per second). Thus, vertical hydraulic conductivity in the Culebra may be created as a result of repository-induced subsidence, although this is expected to be insignificant.

In summary, as a result of observations of subsidence associated with potash mines in the vicinity of the WIPP, the potential for subsidence to create fluid flow paths between the repository and units overlying the Salado has been eliminated from performance assessment calculations on the basis of low probability. The effects of repository-induced subsidence on hydraulic conductivity in the Culebra have been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system.

SCR.2.3.5 <u>Effects of Fluid Pressure Changes</u>

The mechanical effects of gas generation through pressurization and disruption due to gas flow are accounted for in performance assessment calculations.

The mechanical effects of gas generation, including the slowing of creep closure of the repository due to gas **pressurization**, and the fracturing of interbeds in the Salado through **disruption due to gas effects** are accounted for in performance assessment calculations (Sections 6.4.5.2 and 6.4.3.1).

SCR.2.3.6 <u>Effects of Explosions</u>

The potential effects of gas explosions are accounted for in performance assessment calculations. Nuclear explosions have been eliminated from performance assessment calculations on the basis of low probability of occurrence over 10,000 years.

Explosive gas mixtures could collect in the head space above the waste in a closed panel. The most explosive gas mixture potentially generated will be a mixture of hydrogen, methane, and oxygen which will convert to carbon dioxide and water on ignition. This means that there is little likelihood of a **gas explosion** in the long term, because the rooms and panels are expected to become anoxic and oxygen depleted. Compaction through salt creep will also greatly reduce any void space in which the gas can accumulate. Analysis (see Appendix PCS) indicates that the most explosive mixture of hydrogen, methane, and oxygen will be present in the void space approximately 20 years after panel-closure emplacement. This possibility of an explosion prior to the occurrence of anoxic conditions is considered in the design of the operational panel closure. The effect of such an explosion on the DRZ is expected to be no more severe than a roof fall, which is accounted for in the performance assessment calculations (Section SCR.2.3.3).

For a **nuclear explosion** to occur, a critical mass of plutonium would have to undergo rapid compression to a high density. Even if a critical mass of plutonium could form in the system, there is no mechanism for rapid compression. Thus, nuclear explosions have been eliminated from performance assessment calculations on the basis of low probability of occurrence over 10,000 years.

SCR.2.3.7 Thermal Effects

The effects of thermally induced stress, differing thermal expansion of components, and thermal effects on material properties in the repository have been eliminated from performance assessment calculations on the basis of low consequence to performance of the disposal system.

Thermally induced stress could result in pathways for groundwater flow in the DRZ, in the anhydrite layers and marker beds, and through seals, or it could enhance existing pathways. Conversely, elevated temperatures will accelerate the rate of salt creep and mitigate fracture development. Thermal expansion could also result in uplift of the rock and ground surface overlying the repository, and thermal buoyancy forces could lift the waste upward in the salt rock.

The distributions of thermal stress and strain changes depend on the induced temperature field and the **differing thermal expansion of repository components** of the repository, which depends on the components' elastic properties. Potentially, **thermal effects on material properties** (such as permeability and porosity) could affect the behavior of the repository.

Radioactive decay (Section SCR.2.2.2), nuclear criticality (Section SCR.2.2.3), and exothermic reactions (Section SCR.2.5.7) are three possible sources of heat in the WIPP repository.

DOE (1980) estimated that radioactive decay of CH-TRU waste will result in a maximum temperature rise at the center of the repository of 1.6°C at 80 years after waste emplacement (Section SCR.2.2.2). Sanchez and Trellue (1996) have shown that the total thermal load of RH-TRU waste will not significantly affect the average temperature increase in the repository (Section SCR.2.2.2). Temperature increases of about 3°C may occur at the locations of RH-TRU containers of maximum thermal power (60 watts). Material properties, such as porosity and permeability, are insensitive to temperature changes of this order.

Argüello and Torres (1988) evaluated the thermomechanical effects of emplacing RH-TRU waste in the walls of a WIPP waste disposal room. Their analysis assumed that the RH-TRU waste canisters had a thermal power of 60 watts and were emplaced in a disposal room 8 feet (2.44 meters) apart, equivalent to an areal thermal loading of 10 kilowatts per acre (2.5 watts per square meter). This value of the thermal load is significantly greater than the total thermal load of the RH- and CH-TRU waste to be emplaced in the WIPP repository. The thermal and structural responses to the thermal load were evaluated for a six-year simulation period assuming temperature dependent elastic and creep behavior. At the end of this period, the temperature was calculated to have increased by a maximum of about 3°C. Vertical and horizontal room closures were about 4 percent and 7 percent greater, respectively, than under isothermal conditions and changes in stress were negligible. This structural response to temperature change is greater than the expected response in the WIPP repository, because the maximum expected temperature increase from radioactive decay is less than 3°C. Also, the differing thermal expansion of repository components will be insignificant at this magnitude of temperature change. Thus, radioactive decay-induced temperature changes will have negligible effects on the development of the stresses and strains in the repository after waste emplacement.

Thorne and Rudeen (1981) calculated regional uplift and the effects of buoyancy forces resulting from a repository with a thermal power of 2.8 kilowatts per acre (0.7 watts per square meter). The calculated maximum displacement of a point in the repository at the top of the emplacement level was 10.4 millimeters, occurring at about 90 years after emplacement. The maximum surface uplift was calculated to be less than 6 millimeters at about 1,000 years after waste emplacement. This level of uplift will not affect the rock above the repository significantly.

Nuclear criticality has been eliminated from performance assessment calculations on the basis of low probability of occurrence over 10,000 years (Section SCR.2.2.3).

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Temperature increases resulting from exothermic reactions are discussed in Section SCR.2.5.7. Potentially the most significant exothermic reactions are concrete hydration, backfill hydration, and aluminum corrosion. Hydration of the seal concrete could raise the temperature of the concrete to approximately 53°C and that of the surrounding salt to approximately 38°C one week after seal emplacement (see Section SCR.2.5.7.1). The thermomechanical effects of such temperature increases on the performance of the repository seals have been considered in the seal design program (Loken 1994; Loken and Chen 1995). The program has investigated the durability of large-scale concrete seals, and has formulated Salado mass concrete (SMC) with the aim of achieving the seal design targets reported in Wakeley et al. (1995), which include objectives to minimize thermally-induced cracking. According to Wakeley et al. (1995), the SMC will be prepared and emplaced at low temperatures in order to minimize the difference between the maximum concrete temperature and the ambient temperature in the repository. Temperature increases resulting from cement hydration will be low enough to mitigate thermal stresses and eliminate the potential for significant cracking. Loken (1994) and Loken and Chen (1995) examined the thermal and mechanical effects of emplacing large concrete seals in salt at the WIPP and showed that significant cracking of the seals will be unlikely (see Section SCR.2.5.7.1). Thus, thermomechanical effects associated with concrete hydration have been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system. As discussed in Section SCR.2.5.7.2, the maximum temperature rise in the disposal panels as a consequence of backfill hydration will be less than 5°C, resulting from brine inflow following a drilling intrusion into a waste disposal panel. Note that active institutional controls will prevent drilling within the controlled area for 100 years after disposal. By this time, any heat generation by radioactive decay and concrete seal hydration will have decreased substantially, and the temperatures in the disposal panels will have reduced to close to initial values.

Under similar conditions following a drilling event, aluminum corrosion could, at most, result in a short-lived (two years) temperature increase of about 6°C (see Section SCR.2.5.7.3). These calculated maximum heat generation rates resulting from aluminum corrosion and backfill hydration could not occur simultaneously because they are limited by brine availability; each calculation assumes that all available brine is consumed by the reaction of concern. Thus, the temperature rise of 6°C represents the maximum that could occur as a result of any combination of exothermic reactions occurring simultaneously. Temperature increases of this magnitude will have no significant effects on the stress and strain distributions within the disposal system.

In summary, temperature changes in the disposal system will not cause significant thermal expansion in any of the repository components, will not cause significant buoyancy forces, will not result in significant fracture initiation or extension, and will not significantly affect material properties in the disposal system.

Thus, the effects of thermally-induced stress, differing thermal expansion of components, and thermal effects on material properties in the repository have been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system.

SCR.2.3.8 Mechanical Effects on Material Properties

Consolidation of waste is accounted for in performance assessment calculations. Container integrity has been eliminated from performance assessment calculations on the basis of beneficial consequence to the performance of the disposal system. Movement of containers and the mechanical effects of backfill have been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system. Consolidation of seals and mechanical degradation of seals are accounted for in performance assessment calculations. Flow through sealed WIPP investigation boreholes drilled from the surface has been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system. Flow through isolated, unsealed underground boreholes is accounted for in performance assessment calculations.

SCR.2.3.8.1 Consolidation of Waste and Container Performance

Consolidation of waste is accounted for in performance assessment calculations in the modeling of creep closure of the disposal room (Section 6.4.3.1).

Modeling of creep closure and waste dissolution and release conservatively assume immediate container failure. **Container integrity** has been eliminated from performance assessment calculations on the basis of beneficial consequence to the performance of the disposal system.

The chemical conditioners or backfill added to the disposal room will act to resist creep closure. However, calculations have shown that because of the high porosity and low stiffness of the waste and the high waste to potential backfill volume, inclusion of backfill does not significantly decrease the total subsidence in the waste emplacement area or disposal room (Westinghouse 1994). Therefore, the **mechanical effects of backfill** have been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system.

The density of compacted waste is estimated to be around 2,000 kilograms per cubic meter (Sandia WIPP Project 1992, 2-69) and the grain density of halite in the Salado is 2,163 kilograms per cubic meter (Sandia WIPP Project 1992, Vol. 3, 2-20). It is unlikely that this density contrast is sufficiently large to overcome drag forces and thus any resultant **movement of containers** and waste in response to these density contrasts is likely to be minimal. RH-TRU waste is stored in robust, carbon steel-based containers and will generate heat through radioactive decay (Section SCR.2.2.2). This heat may induce density changes in the salt and create buoyancy forces on the containers. Vertical movement of high-level waste containers of a similar density to those at the WIPP in response to thermally-induced density changes has been calculated to be around 1 foot (0.35 meters) (Dawson and Tillerson 1978, 22). Containers at the WIPP will generate much less heat, and will therefore move less. Container movement has therefore been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system.

SCR.2.3.8.2 Repository and Investigation Borehole Seal Performance

Mechanical degradation of seals and **consolidation of seals** are accounted for in performance assessment calculations through the permeability range assumed for the seal system (Section 6.4.4).

There are a large number of boreholes drilled from the surface as part of the site investigation program for the WIPP. The majority of these **investigation boreholes** do not reach the repository horizon and terminate in either the Rustler or in the upper part of the Salado. These shallow boreholes could only act as potential pathways if radionuclides were transported into the Culebra via the shafts or intrusion boreholes. Three-dimensional groundwater flow modeling (Corbet 1995) has demonstrated that vertical flow to the Culebra in the controlled area is downwards and, hence, radionuclides will not migrate up these shallow investigation boreholes to the accessible environment. There are four WIPP investigation boreholes, however, that do intersect the repository horizon within the controlled area (ERDA-9, WIPP-12, WIPP-13, and DOE-1). These could potentially act as pathways to the Culebra or to the surface for radionuclides that migrate along the anhydrite layers a and b, MB138, and MB139.

WIPP investigation boreholes will be sealed using materials and designs in accord with industry standards for the Delaware Basin. A survey of plugging practice (Appendix DEL) shows that the majority of boreholes have a plug below the water-producing zones in the Rustler and a plug at the top of the Bell Canyon. Drilling and abandonment procedures may lead to additional plugs within the Salado. A few boreholes (2 percent of those surveyed), however, have a continuous plug of salt-saturated cement from the top of the Salado to the top of the Bell Canyon. ERDA-9 will be sealed in a similar manner. Other WIPP investigation boreholes will be plugged according to regulatory requirements and standard industry practice. The DOE has committed to plug with cement the portion of these boreholes that penetrate the Salado.

The cement in borehole plugs will react with water that percolates through the plug. If the plug is confined, as is the case for continuous plugs through the Salado and the Castile, the greater volume of the alteration phases will cause a decrease in porosity and permeability, a consequent decrease in the rate of fluid flow through the plug, and hence reduce the rate of alteration. Some corrosion of the steel casing around the concrete will take place, but the overall rate of steel corrosion in a closed environment is insufficient to allow an annulus to form. Salt creep will tend to close any small gaps that do occur in the casing near the base of the section, further reducing the possibility of brine reaching the concrete plug. Although localized alteration may take place, the overall permeability of continuous plugs is assumed to remain equal to or less than the permeability of hardened concrete (5×10^{-17} square meters) for 10,000 years (Appendix MASS, Section MASS.16.3.2).

The cross-sectional area of the WIPP investigation boreholes that penetrate the repository horizon (typically 0.34 square feet [0.03 square meters] each) is small in comparison to that of the shafts (which total about 1025.8 square feet [95.3 square meters]). The effective permeability of the shaft, including the emplaced shaft materials and the DRZ around the shaft, is comparable to the assumed permeability of investigation boreholes. Transport along investigation boreholes will, therefore, be of low consequence in comparison to transport along the shafts, which are explicitly accounted for in performance assessment calculations (Section SCR.2.1.4 and Section 6.4.4).

The design of seals in the investigation boreholes, and the small cross-sectional area of the boreholes in comparison to the shafts, lead to the conclusion that WIPP investigation boreholes can be eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system.

The site investigation program has also involved the drilling of boreholes from within the excavated part of the repository. Following their use for monitoring or other purposes, these **underground boreholes** will be sealed where practical, and salt creep will also serve to consolidate the seals and to close the boreholes. Any boreholes that remain unsealed will connect the repository to anhydrite interbeds within the Salado, and thus provide potential pathways for radionuclide transport. Performance assessment calculations account for fluid flow to and from the interbeds by assuming that the DRZ has a permanently enhanced permeability that allows flow of repository brines into specific anhydrite layers and interbeds. This treatment is also considered to account for the effects of any unsealed boreholes.

SCR.2.4 Subsurface Hydrological and Fluid Dynamic FEPs

SCR.2.4.1 Repository-Induced Flow

Two-phase brine and gas flow and capillary rise (wicking) in the repository and the Salado are accounted for in performance assessment calculations.

Brine inflow to the repository may occur through the DRZ, impure halite, anhydrite layers, or clay layers. Pressurization of the repository through gas generation could limit the amount of brine that flows into the rooms and drifts. Two-phase flow of brine and gas in the repository and the Salado is accounted for in performance assessment calculations (Section 6.4.3.2).

Capillary rise (or **wicking**) is a potential mechanism for liquid migration through unsaturated zones in the repository. Capillary rise in the waste material could affect gas generation rates, which are dependent on water availability. Potential releases due to drilling intrusion are also influenced by brine saturations and therefore by wicking. Capillary rise is therefore accounted for in performance assessment calculations (Section 6.4.3.2).

SCR.2.4.2 Effects of Gas Generation

Fluid flow in the repository and Salado due to gas production is accounted for in performance assessment calculations.

Pressurization of the repository through gas generation could limit the amount of brine that flows into the rooms and drifts. Gas may flow from the repository through the DRZ, impure halite, anhydrite layers, or clay layers. The amount of water available for reactions and microbial activity will impact the amounts and types of gases produced (Section SCR.2.5.1). Gas generation rates, and therefore repository pressure, may change as the water content of the repository changes. Pressure changes and **fluid flow due to gas production** in the repository and the Salado are accounted for in performance assessment calculations through modeling the two-phase flow (Section 6.4.3.2).

SCR.2.4.3 Thermal Effects

Convection has been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system.

Temperature differentials in the repository could initiate **convection**. The resulting thermally-induced brine flow or thermally-induced two-phase flow could influence contaminant transport. Potentially, thermal gradients in the disposal rooms could drive the movement of water vapor. For example, temperature increases around waste located at the edges of the rooms could cause evaporation of water entering from the DRZ. This water vapor could condense on cooler waste containers in the rooms and could contribute to brine formation, corrosion, and gas generation.

Nuclear criticality (Section SCR.2.2.3), radioactive decay (Section SCR.2.2.2), and exothermic reactions (Section SCR.2.5.7) are three possible sources of heat in the WIPP repository.

Nuclear criticality has been eliminated from performance assessment calculations on the basis of low probability of occurrence over 10,000 years (Section SCR.2.2.3).

The DOE (1980, 9-149) estimated that radioactive decay of CH-TRU waste will result in a maximum temperature rise at the center of the repository of 1.6°C at 80 years after waste emplacement (Section SCR.2.2.2). Sanchez and Trellue (1996) have shown that the total thermal load of RH-TRU waste will not significantly affect the average temperature increase in the repository (Section SCR.2.2.2). Temperature increases of about 3°C may occur at the locations of RH-TRU containers of maximum thermal power (60 watts).

Concrete hydration will result in short-term (a few decades) temperature increases in the vicinity of the concrete seals after emplacement. Loken (1994) and Loken and Chen (1995) showed that, one week after seal emplacement, concrete hydration could raise the temperature of the concrete to approximately 53°C and the temperature of the surrounding salt to approximately 38°C.

As discussed in Section SCR.2.5.7.2, the maximum temperature rise in the disposal panels as a consequence of backfill hydration will be less than 5°C, resulting from brine inflow following a drilling intrusion into a waste disposal panel. Note that active institutional controls will prevent drilling within the controlled area for 100 years after disposal. By this time, any heat generation by radioactive decay and concrete seal hydration will have decreased substantially, and the temperatures in the disposal panels will have reduced to close to initial values.

Under similar conditions following a drilling event, aluminum corrosion could, at most, result in a short-lived (two years) temperature increase of about 6°C (see Section SCR.2.5.7.3). These calculated maximum heat generation rates resulting from aluminum corrosion and backfill hydration could not occur simultaneously because they are limited by brine availability; each calculation assumes that all available brine is consumed by the reaction of concern. Thus, the temperature rise of 6°C represents the maximum that could occur as a result of any combination of exothermic reactions occurring simultaneously.

The characteristic velocity, V_i, for convective flow of fluid component *I* in an unsaturated porous medium is given by (from Hicks 1996);

$$V_i \approx -\frac{k_i}{\mu_i}\left(\alpha_i \rho_{i0} g \Delta T\right) ,$$

where α_i (per degree) is the coefficient of expansion of the i^{th} component, k_i is the intrinsic permeability (square meters), μ_i is the fluid viscosity (pascal second), ρ_{i0} (kilograms per cubic meter) is the fluid density at a reference point, g is the acceleration of gravity, and ΔT is the change in temperature. This velocity may be evaluated for the brine and gas phases expected in the waste disposal region.

For a temperature increase of 10°C, the characteristic velocity for convective flow of brine in the DRZ around the concrete shaft seals is approximately 7×10^{-4} meters per year (2×10^{-11} meters per second), and the characteristic velocity for convective flow of gas in the DRZ is approximately 1×10^{-3} meters per year (3×10^{-11} meters per second) (Hicks 1996). For a temperature increase of 25°C, the characteristic velocity for convective flow of brine in the concrete seals is approximately 2×10^{-7} meters per year (6×10^{-15} meters per second), and the characteristic velocity for convective flow of gas in the concrete seals is approximately 3×10^{-7} meters per year (8×10^{-15} meters per second) (Hicks 1996). These values of Darcy velocity are much smaller than the expected values associated with brine inflow to the disposal rooms of fluid flow resulting from gas generation. In addition, the buoyancy forces generated by smaller temperature contrasts in the DRZ, resulting from backfill and concrete hydration and radioactive decay, will be short-lived and insignificant compared to the other driving forces for fluid flow. The short-term concrete seals will be designed to function as barriers to fluid flow for at least 100 years after emplacement, and seal permeability will be minimized (Wakeley et al. 1995). Thus, temperature increases associated with concrete hydration will not result in significant buoyancy driven fluid flow through the concrete seal system. In summary, temperature changes in the disposal system will not cause significant thermal convection. Furthermore, the induced temperature gradients will be insufficient to generate water vapor and drive significant moisture migration.

Temperature effects on fluid viscosity would be most significant in the DRZ surrounding the hydrating concrete seals (where temperatures of approximately 38°C are expected). The viscosity of pure water decreases by about 19 percent over a temperature range of between 27°C and 38°C (Batchelor 1973, 596). Although at a temperature of 27°C, the viscosity of Salado brine is about twice that of pure water (Rechard et al. 1990, a-19), the magnitude of the variation in brine viscosity between 27°C and 38°C will be similar to the magnitude of the variation in viscosity of pure water. The viscosity of air over this temperature range varies by less than 7 percent (Batchelor 1973, 594) and the viscosity of gas in the waste disposal region over this temperature range is also likely to vary by less than 7 percent. The Darcy fluid flow velocity for a porous medium is inversely proportional to the fluid viscosity. Thus, increases in brine and gas flow rates may occur as a result of viscosity variations in the vicinity of the concrete seals. However, these viscosity variations will persist only for a short period in which temperatures are elevated, and, thus, the expected variations in brine and gas viscosity in the waste disposal region will not affect the long-term performance of the disposal system significantly.

In summary, temperature changes in the disposal system will not cause significant thermally-induced two-phase flow. Thermal convection has been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system.

SCR.2.5 Geochemical and Chemical FEPs

SCR.2.5.1 Gas Generation

Gas generation can affect the mechanical behavior of the host rock and engineered barriers, chemical conditions, and brine flow, and, as a result, the transport of radionuclides. Potential gas generation processes include corrosion, microbial degradation, radiolysis, and helium production.

The amount of water available for gas generation will have a major impact on the amounts and types of gases produced. WIPP waste may contain small amounts of water as residual liquid; the WAC require that the waste containers have no free liquids. For storage sites with no capability to repackage waste, approval may be given for containers that contain residual liquids in well-drained containers as long as such residuals do not exceed 1 percent of the volume of the container. Such residual liquids are expected to be an insignificant source of liquid in the repository. Water may also be introduced by the influx of brine from the Salado, as discussed in Section SCR.2.4.1.

The following sections discuss gas generation by microbial degradation, corrosion, radiolysis, and helium production.

SCR.2.5.1.1 Microbial Gas Generation

Microbial gas generation from degradation of organic material is accounted for in performance assessment calculations, and the effects of temperature and biofilm formation on microbial gas generation are incorporated in the gas generation rates used. The effects of pressure and radiation on microbial gas generation have been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system.

Microbial breakdown of cellulosic material, and possibly plastics and other synthetic materials, will produce mainly CO_2, but also N_2O, N_2, H_2S, H_2, and CH_4. The rate of microbial gas production will depend upon the nature of the microbial populations established, the prevailing conditions, and the substrates present. Microbial gas generation from **degradation of organic material** is accounted for in performance assessment calculations.

The following subsections discuss the effects of temperature, pressure, radiation, and biofilms on gas production rates via their control of microbial gas generation processes.

SCR.2.5.1.1.1 Effects of Temperature on Microbial Gas Generation

Calculations and experimental studies of induced temperature distributions within the repository have been undertaken and are described in Section SCR.2.2.2. Numerical analysis suggests that the average temperature increase in the WIPP repository caused by radioactive decay of the emplaced CH- and RH-TRU waste is likely to be less than 3°C (Section SCR.2.2.2).

Temperature increases resulting from exothermic reactions are discussed in Section SCR.2.5.7. Potentially the most significant exothermic reactions are concrete hydration, backfill hydration, and aluminum corrosion. Hydration of the seal concrete could raise the temperature of the concrete to approximately 53°C and that of the surrounding salt to approximately 38°C one week after seal emplacement (see Section SCR.2.5.7.1).

As discussed in Section SCR.2.5.7.2, the maximum temperature rise in the disposal panels as a consequence of backfill hydration will be less than 5°C, resulting from brine inflow following a drilling intrusion into a waste disposal panel. Note that active institutional controls will prevent drilling within the controlled area for 100 years after disposal. By this time, any heat generation by radioactive decay and concrete seal hydration will have decreased substantially, and the temperatures in the disposal panels will have reduced to close to initial values.

Under similar conditions following a drilling event, aluminum corrosion could, at most, result in a short-lived (two years) temperature rise of about 6°C (see Section SCR.2.5.7.3). These calculated maximum heat generation rates resulting from aluminum corrosion and backfill hydration could not occur simultaneously because they are limited by brine availability; each calculation assumes that all available brine is consumed by the reaction of concern. Thus, the temperature rise of 6°C represents the maximum that could occur as a result of any combination of exothermic reactions occurring simultaneously.

Relatively few data exist on the **effects of temperature on microbial gas generation** under expected WIPP conditions. Molecke (1979, 4) summarized microbial gas generation rates observed during a range of experiments. Increases in temperature from ambient up to 40°C or 50°C were reported to increase gas production, mainly via the degradation of cellulosic waste under either aerobic or anaerobic conditions (Molecke 1979, 7). Above 70°C, however, gas generation rates were generally observed to decrease. The experiments were conducted over a range of temperatures and chemical conditions and for different substrates, representing likely states within the repository. Gas generation rates were presented as ranges with upper and lower bounds as estimates of uncertainty (Molecke 1979, 7). Later experiments reported by Francis and Gillow (1994) support the gas generation rate data reported by Molecke (1979). These experiments investigated microbial gas generation under a wide range of possible conditions in the repository. These conditions included the presence of microbial inoculum, humid or inundated conditions, cellulosic substrates, additional nutrients, electron acceptors, bentonite, and initially oxic or anoxic conditions. These experiments were carried out at a reference temperature of 30°C, based on the average temperature expected in the repository. Gas generation rates used in the performance assessment calculations have been derived from available experimental data and are described in Chapter 6.0 (Section 6.4.3.3). The effects of temperature on microbial gas generation are implicitly incorporated in the gas generation rates used.

SCR.2.5.1.1.2 Effects of Pressure on Microbial Gas Generation

Chemical reactions may occur depending on, among other things, the concentrations of available reactants, the presence of catalysts and the accumulation of reaction products, the biological activity, and the prevailing conditions (for example, temperature and pressure). Reactions that involve the production or consumption of gases are often particularly influenced by pressure because of the high molar volume of gases. The effect of high total pressures on chemical reactions is generally to reduce or limit further gas generation.

Few data exist from which the **effects of pressure on microbial gas generation** reactions that may occur in the WIPP can be assessed and quantified. Studies of microbial activity in deep-sea environments suggest (for example, Kato et al. 1994, 94) that microbial gas generation reactions are less likely to be limited by increasing pressures in the disposal rooms than are inorganic gas generation reactions (for example, corrosion). Consequently, the effects of pressure on microbial gas generation have been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system.

SCR.2.5.1.1.3 Effects of Radiation on Microbial Gas Generation

Experiments investigating microbial gas generation rates suggest that the effects of alpha radiation from TRU waste is not likely to have significant effects on microbial activity (Barnhart et al. 1980; Francis 1985). Consequently, the **effects of radiation on microbial gas generation** have been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system.

SCR.2.5.1.1.4 Effects of Biofilms on Microbial Gas Generation

The location of microbial activity within the repository is likely to be controlled by the availability of substrates and nutrients. Biofilms may develop on surfaces where nutrients are concentrated. They consist of one or more layers of cells with extracellular polymeric material and serve to maintain an optimum environment for growth. Within such a biofilm ecosystem, nutrient retention and recycling maximize microbe numbers on the surface (see, for example, Stroes-Gascoyne and West 1994, 9 – 10).

Biofilms can form on almost any moist surface, but their development is likely to be restricted in porous materials. Even so, their development is possible at locations throughout the disposal system. The **effects of biofilms on microbial gas generation** may affect disposal system performance through control of microbial population size and their effects on radionuclide transport.

Molecke (1979, 4) summarized microbial gas generation rates observed during a range of experimental studies. The experiments were conducted over a range of temperatures and chemical conditions and for different substrates representing likely states within the repository. However, the effect of biofilm formation in these experiments was uncertain. Molecke (1979, 7), presented gas generation rates as ranges, with upper and lower bounds as estimates of uncertainty. Later experiments reported by Francis and Gillow (1994) support the gas generation rate data reported by Molecke (1979). Their experiments investigated microbial gas generation under a wide range of possible conditions in the repository. These conditions included the presence of microbial inoculum, humid or inundated conditions, cellulosic substrates, additional nutrients, electron acceptors, bentonite, and initially oxic or anoxic conditions. Under the more favorable conditions for microbial growth established during the experiments, the development of populations of halophilic microbes and associated biofilms was evidenced by observation of an extracellular, carotenoid pigment, bacterioruberin, in the culture bottles (Francis and Gillow 1994, 59). Gas generation rates used in the performance assessment calculations have been derived from available experimental data and are described in Chapter 6.0 (Section 6.4.3.3). The effects of biofilms on microbial gas generation rates are implicitly incorporated in the gas generation rates.

Biofilms may also influence contaminant transport rates through their capacity to retain and thus retard both the microbes themselves and radionuclides. This effect is not accounted for in performance assessment calculations, but is considered potentially beneficial to calculated disposal system performance. Microbial transport is discussed in Section SCR.2.6.4.

SCR.2.5.1.2 <u>Corrosion</u>

Gas generation from metal corrosion is accounted for in performance assessment calculations, and the effects of chemical changes from metal corrosion are incorporated in the gas generation rates used. Galvanic coupling between the waste and metals external to *the repository has been eliminated from performance assessment calculations on the basis of low probability of occurrence over 10,000 years.*

Oxic corrosion of waste drums and metallic waste will occur at early times following closure of the repository and will deplete its oxygen content. Anoxic corrosion will follow the oxic phase and will produce H_2, while consuming water. **Gases from metal corrosion** are accounted for in performance assessment calculations.

The following subsections discuss the effects on gas production rates of galvanic coupling, electrochemical gradients, and chemical changes from metal corrosion.

SCR.2.5.1.2.1 Galvanic Coupling and the Effects of Electrochemical Gradients

Galvanic coupling refers to the establishment of an electrical current through chemical processes. Galvanic coupling could lead to the establishment of potential gradients between metals in the waste form, canisters, and other metals external to the waste form. Such electrochemical effects can potentially influence corrosion processes and therefore gas generation rates and chemical migration.

Metals other than those in the waste form and canisters could potentially include natural metallic ore bodies in the host rock and metallic elements in other parts of the repository. However, the absence of metallic ores in the region (Appendix GCR) allows galvanic coupling between the waste and metals external to the repository to be eliminated from performance assessment calculations on the basis of low probability of occurrence over 10,000 years.

A variety of metals will be present within the repository (for example, waste metals and canisters), and the potential exists for galvanic cells to be established over short distances. As an example, the presence of copper could influence rates of hydrogen gas production resulting from the corrosion of iron.

The precise interactions that may occur are complex and depend on the metals involved, their physical disposition, and the prevailing conditions (for example, salinity). Good physical and electrical contact between the metals involved is critical to the establishment of galvanic cells. Experience with experimental investigations suggests that this condition is unlikely to be achieved in the repository conditions. In the laboratory, significant efforts are required to assure metal-to-metal contact sufficient for galvanic coupling to occur. Such contact is unlikely to occur to a significant extent in the repository. Consequently, given the preponderance of iron over other metals within the repository and the likely passivation of many nonferrous materials, the influence of these electrochemical interactions on corrosion, and therefore gas generation, is expected to be minimal. Therefore, the effects of electrochemical gradients on gas generation from corrosion have been eliminated from performance assessment calculations on the basis of low consequence.

SCR.2.5.1.2.2 Effects of Chemical Changes from Metal Corrosion on Gas Generation Rates

The predominant **chemical effect of corrosion** reactions on the environment of disposal rooms will be to lower the oxidation state of the brines and maintain reducing conditions.

Molecke (1979, 4) summarized gas generation rates that were observed during a range of experiments. The experiments were conducted over a range of temperatures and chemical conditions representing likely states within the repository. Later experiments reported by Telander and Westerman (1993) support the gas generation rate data reported by Molecke (1979). Their experiments investigated gas generation from corrosion under a wide range of possible conditions in the repository. The studies included corrosion of low-carbon steel waste packaging materials in synthetic brines, representative of intergranular Salado brines at the repository horizon, under anoxic (reducing) conditions.

Gas generation rates used in the performance assessment calculations have been derived from available experimental data and are described in Chapter 6.0 (Section 6.4.3.3). The effects of chemical changes from metal corrosion are, therefore, accounted for in performance assessment calculations.

SCR.2.5.1.3 Radiolytic Gas Generation

Gas generation from radiolysis of brine and cellulosics, and helium production, have been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system. The formation and transport of radioactive gases has been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system.

This section discusses gas generation resulting from the radiolysis of brine and cellulosics, helium production, and the formation and transport of radioactive gases.

SCR.2.5.1.3.1 Radiolysis of Brine

Radiolysis of brine in the WIPP disposal rooms, and of water in the waste, will lead to the production of gases and may significantly affect the oxygen content of the rooms. This in turn will affect the prevailing chemical conditions and potentially the concentrations of radionuclides that may be mobilized in the brines.

The overall reaction for the radiolysis of water in the waste and brine is

$$H_2O = H_2 + {}^1/_2 O_2 .$$

However, the production of intermediate oxygen-bearing species that may subsequently undergo reduction, such as H_2O_2, ClO_3^-, and ClO_4^-, will lead to reduced oxygen gas yields.

The remainder of this section is concerned with the physical effects of gas generation by radiolysis of brine.

Reed et al. (1993) studied radiolytic gas generation during experiments lasting between 155 and 182 days. These experiments involved both synthetic brines similar to those sampled from the Salado at the WIPP repository horizon, and brines occurring in reservoirs in the Castile, as well as real brines sampled from the Salado in the repository workings. The brines were spiked with $^{239}Pu(VI)$ at concentrations between 6.9×10^{-9} and 3.4×10^{-4} molal. During these relatively short-term experiments, hydrogen gas was observed as the product of radiolysis. Oxygen gas was not observed; this was attributed to the formation of intermediate oxygen-bearing species. However, given sufficient exposure to alpha-emission, oxygen production may reach 50 percent that of hydrogen.

An estimate of the potential rate of gas generation due to the radiolysis of brine, R_{RAD}, can be made by making the following assumptions:

- Gas production occurs following the reaction above, so that 1.5 moles of gas are generated for each mole of water consumed.

- Gas production occurs as a result of the alpha decay of ^{239}Pu.

- ^{239}Pu concentrations in the disposal room brines are controlled by solubility equilibria.

- All of the dissolved plutonium is ^{239}Pu.

R_{RAD} is then given by

$$R_{RAD} = \frac{1.5 \times 3.15 \times 10^{7} C_{Pu} Sa_{Pu} G \overline{E}_{\alpha} V_B}{N_D N_A},$$

where

R_{RAD}	=	potential rate of gas production (moles per drum per year)
C_{Pu}	=	maximum dissolved concentration of plutonium (molal)
Sa_{Pu}	=	specific activity of ^{239}Pu (5.42×10^{11} becquerels per mole)
$\overline{E}_{\alpha}$	=	average energy of α-particles emitted during ^{239}Pu decay (5.15×10^{6} electron volts)
G	=	number of moles of molecules split per 100 eV
V_B	=	volume of brine in the repository (liters)
N_D	=	number of CH drums in the repository (6.7×10^{5})
N_A	=	Avogadro constant (6.0×10^{23} molecules per mole)

The maximum dissolved concentration of plutonium, C_{Pu} has been taken as 3.0×10^{-4} molal based on the dissolved and colloidal actinide source term for the WIPP as described in Chapter 6.0 (Sections 6.4.3.5 and 6.4.3.6). The value of G used in this calculation has been set at 1.5×10^{-2}, the upper limit of the range of values observed (1.1×10^{-2} to 1.5×10^{-2}) during experimental studies of the effects of radiation on WIPP brines (Reed et al. 1993, 432). A maximum estimate of the volume of brine that could potentially be present in the disposal region has been made from its excavated volume (436,000 cubic meters; Sandia WIPP Project 1992, 3-4). This estimate, in particular, is considered to be highly conservative because it makes no allowance for creep closure of the excavation, or for the volume of waste and backfill that will be emplaced, and takes no account of factors that may limit brine inflow. These parameter values lead to an estimate of the potential rate of gas production due to the radiolysis of brine of 0.6 moles per drum per year.

Assuming ideal gas behavior and repository conditions of 30°C and 14.8 megapascals (lithostatic pressure), this is equivalent to approximately 6.8×10^4 liters per year.

Potential gas production rates from other processes that will occur in the repository are significantly greater than this. For example, under water-saturated conditions, microbial degradation of cellulosic waste has the potential to yield between 1.3×10^6 and 3.8×10^7 liters per year; anoxic corrosion of steels has the potential to yield up to 6.3×10^5 liters per year (Chapter 6.0, Section 6.4.3.3).

In addition to the assessment of the potential rate of gas generation by radiolysis of brine given above, a study of the likely consequences on disposal system performance has been undertaken by Vaughn et al. (1995). A model was implemented in BRAGFLO to estimate radiolytic gas generation in the disposal region according to the equation above.

A set of BRAGFLO simulations was performed to assess the magnitude of the influence of the radiolysis of brine on contaminant migration to the accessible environment. The calculations considered radiolysis of H_2O by 15 isotopes of thorium, plutonium, uranium, and americium.

Conditional complementary cumulative distribution functions (CCDFs) of normalized contaminated brine releases to the Culebra via a human intrusion borehole and the shaft system, as well as releases to the subsurface boundary of the accessible environment via the Salado interbeds, were constructed and compared to the corresponding baseline CCDFs calculated excluding radiolysis.

The comparisons indicated that radiolysis of brine does not significantly affect releases to the Culebra or the subsurface boundary of the accessible environment under disturbed or undisturbed conditions (Vaughn et al. 1995). Although the analysis of Vaughn et al. (1995) used data that are different than those used in the performance assessment calculations, performance assessment estimates of total gas volumes in the repository are similar to those considered in the analysis performed by Vaughn et al. (1995).

Therefore, gas generation by radiolysis of brine has been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system.

SCR.2.5.1.3.2 Radiolysis of Cellulosics

Molecke (1979) compared experimental data on gas production rates caused by **radiolysis of cellulose** and other waste materials with gas generation rates by other processes including bacterial (microbial) waste degradation. The comparative gas generation rates reported by Molecke (1979, 4) are given in terms of most probable ranges, using units of moles per year per drum, for drums of 0.21 cubic meters in volume.

A most probable range of 0.005 to 0.011 moles per year per drum is reported for gas generation due to radiolysis of cellulosic material (Molecke 1979, 4). As a comparison, a most probable range of 0.0 to 5.5 moles per year per drum is reported for gas generation by bacterial degradation of waste.

The data reported by Molecke (1979) are consistent with more recent gas generation investigations made under the WIPP program, and indicate that radiolysis of cellulosic materials will generate significantly less gas than other gas generation processes. Gas generation from radiolysis of cellulosics therefore can be eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system.

SCR.2.5.1.3.3 Helium Production

Within the WIPP, **helium gas production** will occur by the reduction of α-particles (helium nuclei) emitted from the waste. The maximum amount of helium that could be produced can be estimated by assuming that all of the α-particles generated during radioactive decay are converted to helium gas by the following reaction:

$$({}^4_2He^{2+},\ \alpha\text{-}particle) + 2e^- = He_{(g)}\ .$$

The total inventory (I) that may be emplaced in the repository is approximately 9 million curies or 3.3×10^{17} becquerels (see Appendix BIR). Assuming that the inventory continues to yield α-particles at this rate throughout the 10,000-year regulatory period (that is, that the source does not diminish even though the α-particles are produced during radioactive decay), the maximum rate of helium gas produced (R_{He}) may be calculated from

$$R_{He} = \frac{I}{N_A}\ ,$$

where

R_{He} = rate of helium gas production in the repository (mole per second)
I = waste inventory (3.3×10^{17} becquerels)
N_A = Avogadro constant (6.0×10^{23} molecules per mole)

These assumptions regarding the inventory lead to maximum estimates for helium production because, in reality, the total activity will decrease with time and because some of the radionuclides will decay by beta and gamma emission.

Based on the figures and equation given above, $R_{(He)}$ is approximately 5.5×10^{-7} moles per second. Assuming ideal gas behavior and repository conditions of 30°C and 14.8 megapascals (lithostatic pressure), this is equivalent to approximately 3.0 liters per year.

Gas production rates caused by other processes that will occur in the repository are likely to be significantly greater than this. For example, under water-saturated conditions, microbial degradation of cellulosic waste is estimated to yield between 1.3×10^{6} and 3.8×10^{7} liters per year; anoxic corrosion of steels is estimated to yield between 0 and 6.3×10^{5} liters per year (Chapter 6.0, Section 6.4, and Appendix MASS). Even if gas production by these processes were minimal and helium production dominated gas generation, the effects would be of low consequence because of the low total volumes.

Therefore, by estimation of the maximum possible generation rate, the effects of helium production have been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system.

SCR.2.5.1.3.4 Radioactive Gases

Based on the composition of the anticipated waste inventory as described in Appendix BIR, the **radioactive gases** that will be generated in the repository are carbon dioxide (CO_2) and methane (CH_4) containing ^{14}C, and radon (Rn).

Appendix BIR indicates that a small amount of ^{14}C, 2.88 grams, or 12.85 curies, will be disposed in the WIPP. This amount is insignificant in comparison with the 40 CFR § 191.13 cumulative release limit for ^{14}C, estimated to be 525 curies (Appendix BIR).

Notwithstanding this comparison, consideration of transport of radioactive gases could potentially be necessary in respect of the 40 CFR § 191.15 individual protection requirements. ^{14}C may partition into carbon dioxide and methane formed during microbial degradation of cellulosic and other organic wastes (for example, rubbers and plastics). However, total fugacities of carbon dioxide in the repository are expected to be very low because of the action of the MgO backfill which will lead to incorporation of carbon dioxide in solid $MgCO_3$. Similarly, interaction of carbon dioxide with cementitious wastes will limit carbon dioxide fugacities by the formation of solid $CaCO_3$. Thus, because of the formation of solid carbonate phases in the repository, significant transport of ^{14}C as $^{14}CO_2$ has been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system.

Potentially significant volumes of methane may be produced during the microbial degradation of cellulosic waste. However, volumes of $^{14}CH_4$ will be small given the low total inventory of ^{14}C, and the tendency of ^{14}C to be incorporated into solid carbonate phases in the repository. Therefore, although transport of ^{14}C could occur as $^{14}CH_4$, this effect has been eliminated from the current performance assessment calculations on the basis of low consequence to the performance of the disposal system.

Radon gas will contain proportions of the alpha emitters ^{219}Rn, ^{220}Rn, and ^{222}Rn. All of these have short half-lives, but ^{222}Rn is potentially the most important because it is produced from the abundant waste isotope, ^{238}Pu, and because it has the longest half-life of the radon isotopes ($\approx$ 4 days). ^{222}Rn will exhibit secular equilibrium with its parent ^{226}Ra, which has a half-life of 1.6×10^3 years. Consequently, ^{222}Rn will be produced throughout the 10,000-year regulatory time period. Conservative analysis of the potential ^{222}Rn inventory suggests activities of less than 716 curies at 10,000 years (Bennett 1996).

Direct comparison of the estimated level of ^{222}Rn activity with the release limits specified in 40 CFR § 191.13 cannot be made because the release limits do not cover radionuclides with half-lives less than 20 years. For this reason, production of radon gas can be eliminated from the performance assessment calculations on regulatory grounds. Notwithstanding this regulatory argument, the small potential radon inventory means that the formation and transport of radon gas can also be eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system.

SCR.2.5.2 Chemical Speciation

Chemical speciation is accounted for in performance assessment calculations in the estimates of radionuclide solubility in the disposal rooms, and the degree of chemical retardation estimated during contaminant transport. The effects of cementitious seals on chemical speciation have been eliminated from performance assessment calculations on the basis of beneficial consequence to the performance of the disposal system. The effects of reaction kinetics in chemical speciation reactions have been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system.

Chemical speciation refers to the form in which elements occur under a particular set of chemical or environmental conditions. Conditions affecting chemical speciation include the temperature, pressure, and salinity (ionic strength) of the water in question. The importance of chemical speciation lies in its control of the geochemical reactions likely to occur and the consequences for actinide mobility.

The effects of reaction kinetics in aqueous systems are discussed by Lasaga et al. (1994) who suggest that in contrast to many heterogeneous reactions, homogeneous aqueous geochemical speciation reactions involving relatively small inorganic species occur rapidly and are accurately described by thermodynamic equilibrium models that neglect explicit consideration of reaction kinetics (for example, Lasaga et al. 1994, 2361). Consequently, the **kinetics of speciation** reactions have been eliminated from performance assessment calculation on the basis of low consequence to the performance of the disposal system.

The following subsections discuss chemical speciation in the disposal rooms, shaft seals, and the Culebra.

SCR.2.5.2.1 Disposal Room

The concentrations of radionuclides that dissolve in any brines present in the disposal rooms after repository closure will depend on the stability of the chemical species that form under the prevailing conditions (for example, temperature, pressure, and ionic strength). The method used to derive radionuclide solubilities in the disposal rooms (see Section 6.4.3.5) considers the expected conditions. The MgO backfill will buffer pH values in the disposal room to between 9 and 10. Thus, chemical speciation is accounted for in performance assessment calculations in the estimates of radionuclide solubility in the disposal rooms.

SCR.2.5.2.2 Repository Seals

Certain repository materials have the potential to interact with groundwater and significantly alter the chemical speciation of any radionuclides present. In particular, extensive use of cementitious materials in the seals may have the capacity to buffer groundwaters to extremely high pH (for example, Bennett et al. 1992, 315 – 325). At high pH values, the speciation and adsorption behavior of many radionuclides is such that their dissolved concentrations are reduced in comparison with near-neutral waters. This effect reduces the migration of radionuclides in dissolved form. The effects of cementitious seals on groundwater chemistry have been eliminated from performance assessment calculations on the basis of beneficial consequence to the performance of the disposal system.

SCR.2.5.2.3 Culebra

Chemical speciation will affect actinide retardation in the Culebra. The dependence of actinide retardation on speciation in the Culebra is accounted for in performance assessment calculations by sampling over ranges of distribution coefficients (K_ds). The ranges of K_ds are based on the range of groundwater compositions and speciation in the Culebra, including consideration of nonradionuclide solutes. The methodology used to simulate sorption in the Culebra is described in Section 6.4.6.2.1.

SCR.2.5.3 Precipitation and Dissolution

Waste dissolution and the release of radionuclides in the disposal rooms are accounted for in performance assessment calculations. The effect of reaction kinetics in controlling the rate of *waste dissolution within the disposal rooms has been eliminated from performance assessment calculations on the basis of beneficial consequence to the performance of the disposal system. The formation of radionuclide bearing precipitates from groundwaters and brines and the associated retardation of contaminants have been eliminated from performance assessment calculations on the basis of beneficial consequence to the performance of the disposal system.*

Dissolution of waste and **precipitation** of secondary minerals are relevant because of their control of the concentrations of radionuclides in any brines and groundwaters and the rates of contaminant transport. Waste dissolution is accounted for in performance assessment calculations. Mineral dissolution and precipitation processes also have the potential to alter rock permeabilities and, hence, groundwater flow. Mineral precipitation, for example, may block pores or fill fractures, resulting in modification of the groundwater flow field.

At low temperatures, precipitation and dissolution reactions are caused by changes in fluid chemistry that result in chemical undersaturation or oversaturation (Bruno and Sandino 1987, 12). Precipitation can be divided into two stages: nucleation and crystal growth. Following nucleation, growth rates depend on the rates of surface processes and the transport of materials to the site of growth. The style of mineral dissolution often depends on whether the rate-controlling process is a surface reaction or is related to the transport of material away from the site of dissolution. The former case may result in selective dissolution along crystallographically controlled features, whereas the latter may lead to rapid bulk dissolution (Berner 1981, 117). Thus, it is expected that a range of kinetic behavior will be exhibited by different mineral precipitation and dissolution reactions in different geochemical systems.

The following subsections discuss dissolution of waste in the disposal rooms and precipitation in geological units of the WIPP disposal system.

SCR.2.5.3.1 <u>Disposal Room</u>

Waste dissolution in the disposal rooms is accounted for in performance assessment calculations in the estimates of radionuclide solubility used. The WIPP actinide source term model is described in detail in Section 6.4.3.5. The assumption of equilibrium waste dissolution represents a conservative approach to predicting radionuclide concentrations in the disposal room brines because it yields maximum concentration estimates. The **kinetics of dissolution** within the disposal rooms has been eliminated from performance assessment calculations on the basis of beneficial consequence to the performance of the disposal system.

SCR.2.5.3.2 <u>Geological Units</u>

During groundwater flow, any radionuclide precipitation processes that occur will lead to reduced contaminant transport. No credit is given to the potentially beneficial occurrence of such reactions in performance assessment calculations. The formation of radionuclide-bearing precipitates from groundwaters and brines and the associated retardation of contaminants has been eliminated from performance assessment calculations on the basis of beneficial consequence to the performance of the disposal system. The **kinetics of precipitation** reactions have, therefore, also been eliminated from performance assessment calculations because no credit is taken for precipitation reactions. Dissolution of minerals in the Culebra and other geological units is discussed in Section SCR.1.1.5.

SCR.2.5.4 <u>Sorption</u>

Sorption within the disposal rooms, which would serve to reduce radionuclide concentrations, has been eliminated from performance assessment calculations on the basis of beneficial consequence to the performance of the disposal system. The effects of sorption processes in shaft seals and panel closures have been eliminated from performance assessment calculations on the basis of beneficial consequence to the performance of the disposal system. Sorption within the Culebra and the Dewey Lake is accounted for in performance assessment calculations. Sorption processes within other geological units of the disposal system have been eliminated from performance assessment calculations on the basis of beneficial consequence to the performance of the disposal system. Mobile adsorbents (for example, microbes and humic acids), and the sorption of radionuclides at their surfaces, are accounted for in performance assessment calculations in the estimates of the concentrations of actinides that may be carried. The potential effects of reaction kinetics in adsorption processes and of changes in sorptive surfaces are accounted for in performance assessment calculations.

Sorption may be defined as the accumulation of matter at the interface between a solid and an aqueous solution. Within performance assessment calculations, including those made for the WIPP, the use of isotherm representations of **actinide sorption** prevails because of their computational simplicity in comparison with other models (Serne 1992, 238 – 239).

The mechanisms that control the **kinetics of sorption** processes are, in general, poorly understood. Often, sorption of inorganic ions on mineral surfaces is a two-step process consisting of a short period (typically minutes) of diffusion-controlled, rapid uptake, followed by slower processes (typically weeks to months) including surface rearrangement, aggregation and precipitation, and solid solution formation (Davis and Kent 1990, 202). Available data concerning rates of sorption reactions involving the important radionuclides indicate that, in general, a range of kinetic behavior is to be expected.

The relevance to the WIPP of sorption reaction kinetics lies in their effects on chemical transport. Sorption of waste contaminants to static surfaces of the disposal system such as seals and host rocks acts to retard chemical transport. Sorption of waste contaminants to potentially mobile surfaces, such as colloids, however, may act to enhance chemical transport, particularly if the kinetics of contaminant desorption are slow or the process is irreversible (nonequilibrium).

The following subsections discuss sorption in the disposal rooms, shaft seals, panel closures, the Culebra, and other geological units of the WIPP disposal system. Sorption on colloids, microbes, and particulate material is also discussed.

SCR.2.5.4.1 Disposal Room

The concentrations of radionuclides that dissolve in waters entering the disposal room will be controlled by a combination of sorption and dissolution reactions. However, because sorption processes are surface phenomena, the amount of material that is likely to be involved in sorption mass transfer processes will be small relative to that involved in the bulk dissolution of waste. WIPP performance assessment calculations therefore assume that dissolution reactions control radionuclide concentrations. Sorption on waste, containers, and backfill within the disposal rooms, which would serve to reduce radionuclide concentrations, has been eliminated from performance assessment calculations on the basis of beneficial consequence to the performance of the disposal system.

SCR.2.5.4.2 Shaft Seals and Panel Closures

Chapter 3.0 and Appendix SEAL describe the seals that are to be placed at various locations in the access shafts and waste panel access tunnels. The materials to be used include crushed salt, bentonite clay, and cementitious grouts. Of these, the latter two in particular possess significant sorption capacities. No credit is given for the influence of sorption processes that may occur in seal materials and their likely beneficial effects on radionuclide migration rates. The effects of sorption processes in shaft seals and panel closures have been eliminated from performance assessment calculations on the basis of beneficial consequence to the performance of the disposal system.

SCR.2.5.4.3 Culebra

Sorption within the Culebra is accounted for in performance assessment calculations as discussed in Section 6.4.6.2. The model used comprises an equilibrium, sorption isotherm approximation, employing constructed cumulative distribution functions (CDFs) of distribution coefficients (K_ds) applicable to dolomite in the Culebra. The potential effects of reaction kinetics in adsorption processes are encompassed in the ranges of K_ds used. The geochemical speciation of the Culebra groundwaters and the effects of **changes in sorptive surfaces** are implicitly accounted for in performance assessment calculations for the WIPP in the ranges of K_ds used.

SCR.2.5.4.4 Other Geological Units

During groundwater flow, any radionuclide sorption processes that occur between dissolved or colloidal actinides and rock surfaces will lead to reduced rates of contaminant transport. The sorptive capacity of the Dewey Lake is sufficiently large to prevent any radionuclides that enter it from being released to the accessible environment over 10,000 years (Wallace et al.

1995). Thus, sorption within the Dewey Lake is accounted for in performance assessment calculations as discussed in Section 6.4.6.6. No credit is given to the potentially beneficial occurrence of sorption in other geological units outside the Culebra. Sorption processes within other geological units of the disposal system have been eliminated from performance assessment calculations on the basis of beneficial consequence to the performance of the disposal system.

SCR.2.5.4.5 *Sorption on Colloids, Microbes, and Particulate Material*

The interactions of sorption processes with colloidal, microbial, or particulate transport are complex. Neglecting sorption of contaminants on immobile surfaces in the repository shafts and Salado (for example, the clays of the Salado interbeds) is a conservative approach because it leads to overestimated transport rates. However, neglecting sorption on potentially mobile adsorbents (for example, microbes and humic acids) cannot be shown to be conservative with respect to potential releases, because mobile adsorbents may act to transport radionuclides sorbed to them. Consequently, the concentrations of actinides that may be carried by mobile adsorbents are accounted for in performance assessment calculations (see Section 6.4.3.6).

SCR.2.5.5 Reduction-Oxidation Chemistry

The effects of reduction-oxidation reactions related to metal corrosion on reduction-oxidation conditions are accounted for in performance assessment calculations. Reduction-oxidation reaction kinetics are accounted for in performance assessment calculations. The migration of reduction-oxidation fronts through the repository has been eliminated from performance assessment calculations on the basis of low probability of occurrence over 10,000 years. The formation of localized reducing zones has been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system.

This section considers aspects of the reduction-oxidation chemistry of groundwaters at the WIPP site.

SCR.2.5.5.1 *Reduction-Oxidation Kinetics*

In general, investigation of the reduction-oxidation couples present in aqueous geochemical systems suggests that most reduction-oxidation reactions are not in thermodynamic equilibrium (Wolery 1992, 27). The lack of data characterizing the rates of reactions among trace element reduction-oxidation couples leads to uncertainty in elemental speciation. This uncertainty in **reduction-oxidation kinetics** is accounted for in performance assessment calculations in the dissolved actinide source term model (see Section 6.4.3.5), which estimates the probabilities that particular actinides occur in certain oxidation states.

SCR.2.5.5.2 Corrosion

Other than gas generation, which is discussed in Section SCR.2.5.1, the main **effect of metal corrosion** will be to influence the chemical conditions that prevail within the repository. Ferrous metals will be the most abundant metals in the WIPP, and these will corrode on contact with any brines entering the repository. Initially, corrosion will occur under oxic conditions owing to the atmospheric oxygen present in the repository at the time of closure. However, consumption of the available oxygen by corrosion reactions will rapidly lead to anoxic (reducing) conditions. These changes and controls on conditions within the repository will affect the chemical speciation of the brines and may affect the oxidation states of the actinides present. Changes to the oxidation states of the actinides will lead to changes in the concentrations that may be mobilized during brine flow. The oxidation states of the actinides are accounted for in performance assessment calculations by the use of parameters that describe probabilities that the actinides exist in particular oxidation states and, as a result, the likely actinide concentrations.

SCR.2.5.5.3 Reduction-oxidation Fronts

The development of **reduction-oxidation fronts** in the disposal system may affect the chemistry and migration of radionuclides. Reduction-oxidation fronts separate regions that may be characterized, in broad terms, as having different oxidation potentials. On either side of a reduction-oxidation front, the behavior of reduction-oxidation-sensitive elements may be controlled by different geochemical reactions. Elements that exhibit the greatest range of oxidation states (for example, Pu, U, Np) will potentially be the most affected by reduction-oxidation front development and migration. The migration of reduction-oxidation fronts may occur as a result of diffusion processes, or in response to groundwater flow, but will be restricted by the occurrence of heterogeneous buffering reactions (for example, certain mineral dissolution and precipitation reactions). Indeed, these buffering reactions cause the typically sharp, distinct nature of reduction-oxidation fronts.

Within the repository, **localized reducing zones**, bounded by reduction-oxidation fronts, may develop centered on metals undergoing corrosion. However, the formation of such zones would be of low consequence to disposal system performance owing to the small scale over which these zones and associated reduction-oxidation fronts could exert an influence on radionuclide migration. The formation of localized reducing zones has therefore been eliminated from performance assessment calculations on the basis of low consequence.

Of greater significance is the possibility that the flow of fluids having different oxidation potentials from those established within the repository might lead to the development and migration of a large-scale reduction-oxidation front. Reduction-oxidation fronts have been observed in natural systems to be the loci for both the mobilization and concentration of radionuclides, such as uranium. For example, during investigations at two uranium deposits at Poços de Caldas, Brazil, uranium was observed by Waber (1991) to be concentrated along reduction-oxidation fronts at the onset of reducing conditions by its precipitation as UO_2, the less soluble reduced form, U(IV), of the metal. In contrast, studies of the Alligator Rivers uranium deposit in Australia by Snelling (1992, 21 – 22) indicated that the movement of the relatively oxidized weathered zone downwards through the primary ore body as the deposit was eroded and gradually exhumed led to the formation of secondary uranyl-silicate minerals and the mobilization of uranium in its more soluble U(VI) form in near-surface waters. The available geochemical evidence from these sites suggested that the reduction-oxidation fronts had migrated only slowly, at most on the order of a few tens of meters per million years. These rates of migration were controlled by a range of factors including the rates of erosion, infiltration of oxidizing waters, geochemical reactions, and diffusion processes.

The migration of large-scale reduction-oxidation fronts through the repository as a result of regional fluid flow is considered unlikely over the regulatory period on the basis of comparison with the slow rates of reduction-oxidation front migration suggested by natural system studies. This comparison is considered conservative because the relatively impermeable nature of the Salado suggests that reduction-oxidation front migration rates at the WIPP are likely to be slower than those observed in the more permeable lithologies of the natural systems studied. Large-scale reduction-oxidation fronts have therefore been eliminated from performance assessment calculations on the basis of low probability of occurrence over 10,000 years.

SCR.2.5.6 Organic Complexation

The effects of anthropogenic organic complexation reactions, including the effects of organic ligands, have been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system. The presence of humic and fulvic acids is incorporated in performance assessment calculations.

The formation of aqueous complexes between radionuclides and organic materials has the potential to enhance the total dissolved contaminant load, and thus the potential for contaminant migration (Tipping 1993, 520). Both naturally occurring and anthropogenic organic materials may be important and include

- anthropogenic organics associated with the waste (for example, acetate, citrate, oxylate, ethylene diamine tetra-acetate [EDTA]), and

- naturally occurring high molecular weight organics, including humin, **humic, and fulvic acids** derived from soil waste.

The stability of radionuclide organic complexes is affected by the concentration of complexants and environmental factors. In general, complexing is favored by increased concentration of **organic ligands**, increased pH, and decreased ionic strength.

In natural systems such as soils, rocks, and groundwaters where many phases and reactive surfaces exist, individual slow reactions may limit subsequent chemical processes. Biological uptake of radionuclides and other toxic substances may be limited by the rates of complex dissociation; for certain systems (for example, soils) true equilibrium may never be attained (for example, Rate et al. 1993, 1408). The limited data that exist concerning the **kinetics of organic complexation** reactions indicate that a range of behavior is to be expected, depending on the materials involved and the prevailing chemical conditions. For example, studies of the reactions of certain metals with natural humic materials indicate that desorption rates are influenced by changes in pH, metal and humic concentration ratio, ionic strength, and absolute reaction time (Rate et al. 1993, 1414).

The basis for eliminating anthropogenic organics from performance assessment calculations is described in Appendix SOTERM (Section SOTERM.5).

The occurrence of humic and fulvic acids is incorporated in performance assessment calculations in the models for radionuclide transport by humic colloids (see Section 6.4.6.2.2).

SCR.2.5.7 Exothermic Reactions

The thermal effects of exothermic reactions, including concrete hydration, have been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system.

Exothermic reactions liberate heat and will alter the temperature of the disposal system and affect the properties of the repository and surrounding materials. Dissipation of heat by conduction through the host rock will act to limit any overall temperature change.

Dependent on the amount and rate of energy release, the geometry of the heat source, the thermal conductivities of the surrounding rocks, and any influence of groundwater or brine flow on heat transport, these exothermic reactions may lead to elevated temperatures. Elevated temperatures may influence the rate of salt creep in the surrounding rock, alter the geochemistry of minerals and waters or brines in the system, and lead to cracking of the seals.

In the WIPP, a range of different types of reactions will occur, including corrosion and gas generation, waste dissolution, and concrete seal and backfill hydration, liberating different amounts of heat.

The amount of heat liberated by the different reactions will depend on the extent of reaction that occurs and the enthalpy of the reactions themselves. The former will depend on the inventory of materials emplaced in the WIPP and the subsequent chemical evolution of the repository system. The latter can be assessed by considering typical enthalpies for the reaction types of interest.

Even though there is uncertainty surrounding the extent of reactions that will occur, consideration of typical reaction enthalpies suggests that the concrete and backfill hydration reactions have the greatest potential to evolve significant amounts of heat (Bennett et al.

1996). The effects of these processes on the WIPP are discussed further below. By contrast, the thermal effects of waste dissolution and gas generation by corrosion will be of low consequence. Potential heat generation from nuclear criticality is discussed in Section SCR.2.2.3 and heat generation from radioactive decay is discussed in Section SCR.2.2.2.

SCR.2.5.7.1 Elevated Temperatures as a Result of Concrete Hydration

Elevated temperatures in the concrete seals may influence the rate of salt creep in the surrounding rock, alter the geochemistry of minerals and waters or brines in the system, and lead to cracking of the seals.

Concrete hydration reactions are known to proceed for extended periods (perhaps thousands of years); however, the rates of these reactions decrease with time and, within the WIPP, the greatest evolution of heat will occur during the short period following seal emplacement and repository closure. A quantitative analysis of the thermal effects of emplacing large concrete seals in salt at the WIPP was made by Loken (1994) and Loken and Chen (1995). The analysis suggests that the energy released by the hydration of the seal concrete could raise the temperature of the concrete to approximately 53° C, and that of the surrounding salt to approximately 38°C, one week after seal emplacement. Loken (1994) and Loken and Chen (1995) also examined the potential for cracking of the seals in response to short-term stresses that could develop as a result of thermal expansion of the concrete and long-term stresses caused by creep of the surrounding salt. At both time scales, radially compressive, horizontal stresses are likely to develop in the concrete due to the presence of the surrounding salt. The magnitude of these stresses caused by short-term thermal pulse was calculated to be less than 9.2 megapascals, well below the design compressive strength of the concrete (which for SMC is 31 megapascals). Maximum long-term stresses will develop in the deepest parts of the seals where lithostatic pressure is greatest (14.8 megapascals). Again, these are well below the design compressive strength of the concrete (31 megapascals). Loken's (1994) and Loken and Chen's (1995) analyses also considered potential vertical stresses in the concrete seals. The magnitude of these stresses depends on the thermal history of the seal and the weight of overburden present. The calculations indicated that 50 years after seal emplacement the thermal changes in the seals could lead to maximum tensile stresses of approximately 3 megapascals. Even for the shallowest parts of the shaft seal system, these stresses will be less than the weight of the overburden (6.0 megapascals), making tensile cracking of the seals unlikely.

Thus, Loken's (1994) and Loken and Chen's (1995) analyses confirm that any temperature changes associated with concrete hydration will occur at early times (at most some decades) after repository closure and suggest that significant cracking of the seals will be unlikely. The effects of any minor thermal cracking of concrete seals on seal permeability are accounted for in performance assessment calculations via the range of seal permeabilities used.

WIPP waste contains cement that is used to solidify liquids, particulates, and sludges. All the waste to be emplaced at the WIPP will contain a total of about 8.5×10^6 kilograms of cement

(Bennett et al. 1996). This is equivalent to about 1.5×10^7 moles of CaO per waste disposal panel, representing the cement as CaO. Although a substantial amount of hydration may occur prior to waste disposal, this process will continue at a slower rate after disposal. Concrete hydration can be described by the reaction

$$CaO + H_2O = Ca(OH)_2$$

Disregarding the hydration that will occur prior to disposal and assuming a brine inflow rate of 200 cubic meters per year (the maximum calculated rate, which occurs for the scenario involving an E1 drilling event at 350 years after disposal), the reaction rate of concrete hydration in the panel will be about 1.1×10^7 moles per year, and the reaction could continue for about 1.4 years. Concrete hydration in the waste will generate a thermal load of about 23 kilowatts, based on a reaction enthalpy of −65 kilojoules per mole. Bennett et al. (1996) estimated that the maximum temperature that could be generated by concrete hydration of the waste within a panel is about 2°C. Such a temperature rise will have an insignificant effect on the performance of the disposal system, as discussed further in Sections SCR.2.3.7 (thermally-induced stress), SCR.2.4.3 (thermal convection), SCR.2.5.1.1 (gas generation), and SCR.2.7.3 (thermochemical transport).

The potential effects of elevated temperatures on chemical reactions in the seals and surrounding regions include increased actinide solubilities and alteration of mineral assemblages leading to altered sorption characteristics. Despite the potential for such effects to occur, the short duration of the thermal pulse caused by concrete hydration is such that it will not significantly affect actinide transport in the long term. Sorption within the seals has been eliminated from performance assessment calculations on the basis of beneficial consequence to the performance of the disposal system. Consequently, changes to the sorption characteristics of the seals can also be eliminated from performance assessment calculations.

Thus, the effects of exothermic concrete hydration reactions have been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system.

SCR.2.5.7.2 *Elevated Temperatures as a Result of Backfill Hydration*

The potential for the development of elevated temperatures in the repository as a result of exothermic backfill hydration reactions has been assessed by Bennett et al. (1996). In their analysis, Bennett et al. (1996) made the following assumptions:

- Hydration of the backfill can be described by the reaction

$$MgO + H_2O = Mg(OH)_2 .$$

- Reaction will proceed rapidly so that the rate of heat generation will be controlled by the rate of brine inflow to the repository.

- Reaction will occur uniformly throughout the repository so that all brine entering will contact and react with backfill.

- All of the backfill emplaced will undergo hydration.

The maximum calculated rate of brine inflow into a panel (about 200 cubic meters per year) occurs for the scenario involving an E1 drilling event at 350 years after disposal. The molar density of water is 5.56×10^4 moles per cubic meter and thus the reaction rate of backfill hydration in the panel will be 1.1×10^7 moles per year. Backfill hydration will generate a thermal load of about 13 kilowatts, based on a reaction enthalpy of 38 kilojoules per mole. There will be about 2×10^8 moles MgO emplaced per panel and thus the reaction could continue for about 20 years if sufficient brine was available. Bennett et al. (1996) estimated the maximum temperature that could be generated by backfill hydration within a panel for such a thermal load. Assuming heat loss will occur by conduction through the salt forming the roof and floor of the panel and that heat losses through the side walls are negligible, the maximum temperature rise in a panel, as a consequence of backfill hydration would be less than 5°C. This magnitude of temperature rise will have an insignificant effect on the performance of the disposal system, as discussed further in Sections SCR.2.3.7 (thermally-induced stress), SCR.2.4.3 (thermal convection), SCR.2.5.1.1 (gas generation), and SCR.2.7.3 (thermochemical transport).

The potential effects of elevated temperatures on chemical reactions in the disposal rooms and surrounding regions include increased actinide solubilities and alteration of mineral assemblages leading to altered sorption characteristics. Despite the potential for such effects to occur, the small temperature rise caused by backfill hydration is such that it will not significantly affect the chemical behavior of the actinides beyond the range of uncertainty considered in estimation of the actinide source term (Section 6.4.3.5). Sorption within the backfill has been eliminated from performance assessment calculations on the basis of beneficial consequence to the performance of the disposal system. Consequently, changes to the sorption characteristics of the backfill can also be eliminated from performance assessment calculations.

Thus, the effects of exothermic backfill hydration reactions have been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system.

SCR.2.5.7.3 *Elevated Temperatures as a Result of Other Exothermic Reactions*

Bennett et al. (1996) also considered the potential effects on temperature of a number of other exothermic reactions in the repository. These included backfill carbonation, microbial degradation, and aluminum corrosion.

Backfill carbonation will be limited by microbial CO_2 production; the maximum rate of CO_2 production is expected to be 2.9×10^5 moles per year. Backfill carbonation can be described by the reaction

$$Mg(OH)_2 + CO_2(g) = MgCO_3 + H_2O$$

Backfill carbonation will generate a thermal load of about 0.7 kilowatts, based on a reaction enthalpy of −77 kilojoules per mole. About 3.6×10^7 moles CO_2 could be produced in a single panel and thus the reaction could continue for about 125 years. Bennett et al. (1996) estimated the maximum temperature that could be generated by backfill carbonation within a panel to be about 0.6°C.

The maximum reaction rate for microbial degradation in a panel will be about 1×10^5 moles per year and the inventory is about 1.2×10^7 moles $C_6H_{10}O_5$ per panel. Microbial degradation can be described by the reaction

$$C_6H_{10}O_5 + H_2O = 3CH_4 + CO_2$$

This reaction could continue for about 120 years. Microbial degradation will generate a thermal load of about 1 kilowatt, based on a reaction enthalpy of −312 kilojoules per mole. Bennett et al. (1996) estimated the maximum temperature that could be generated by microbial degradation within a panel to be about 0.8°C. Aluminum corrosion can be described by the reaction

$$Al + 3H_2O = Al(OH)_3 + 1.5H_2$$

Thus, the rate of corrosion of aluminum will be controlled by brine availability. The reaction rate of aluminum corrosion in the panel will be about 0.4×10^7 moles per year, assuming a brine inflow rate of 200 cubic meters per year (1.1×10^7 moles per year). This rate of brine inflow represents the maximum calculated rate, which occurs for the scenario involving an E1 drilling event at 350 years after disposal. About 8×10^6 moles of aluminum will be emplaced in each panel and thus aluminum corrosion could continue for two years.

Aluminum corrosion will generate a thermal load of about 51 kilowatts for a reaction enthalpy of −434 kilojoules per mole. Bennett et al. (1996) estimated the maximum temperature that could be generated by aluminum corrosion within a panel to be about 6°C.

These calculated temperature rises resulting from backfill carbonation, microbial degradation, and aluminum corrosion will not have a significant effect on the performance of the disposal system, as discussed further in Sections SCR.2.3.7 (thermally-induced stress), SCR.2.4.3 (thermal convection), SCR.2.5.1.1 (gas generation), and SCR.2.7.3 (thermochemical transport).

SCR.2.5.8 Chemical Effects on Material Properties

The effects of chemical degradation of seals and of microbial growth on concrete are accounted for in performance assessment calculations. The effects on material properties of the chemical degradation of backfill have been eliminated from performance assessment calculations on the basis of low consequence.

The concrete used in the seal systems will degrade due to chemical reaction with the infiltrating groundwater. Degradation could lead to an increase in permeability of the seal system. The main uncertainties with regard to cement degradation rates at the WIPP are the effects of groundwater chemistry, the exact nature of the cementitious phases present, and the rates of brine infiltration. The performance assessment calculations take a conservative approach to these uncertainties by assuming a large increase in permeability of the concrete seals only a few hundred years after closure. These permeability values are based on seal design considerations and consider the potential effects of degradation processes. Therefore, the effects of **chemical degradation of seals** are accounted for in performance assessment calculations through the CDFs used for seal material permeabilities.

Concrete can be inhabited by alkalophilic bacteria which could produce acids thereby accelerating the seal degradation process. Nitrification processes, which will produce nitric acid, tend to be aerobic, and will be further limited at the WIPP by the low availability of ammonium in the brines (Pedersen and Karlsson 1995, 75). Because of the limitations on growth because of the chemical conditions, it is likely that the effects of **microbial growth on concrete** will be small. The effects of such microbial activity on seal properties are, therefore, implicitly accounted for in performance assessment calculations through the CDFs used for seal material permeabilities.

Degradation of the chemical conditioners or backfill added to the disposal room is a prerequisite of their function in buffering the chemical environment of the disposal room (Section SCR.2.5.2). However, the chemical reactions and dissolution involved will change the physical properties of the material. Because the mechanical and hydraulic characteristics of the backfill have been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system, the effects of the **chemical degradation of backfill** on material properties have been eliminated from performance assessment calculations on the same basis.

SCR.2.6 Contaminant Transport Mode FEPs

Following waste emplacement brine may contact the waste and radionuclides will dissolve. Radionuclide mobility will be affected by radionuclide speciation, solubility, sorption, and precipitation. Chemical and microbial decomposition of organics in the waste may result in the transport of some radionuclides as organic complexes, colloids, and particulate material. Radionuclides bound to microbes might also be transported. Potentially, radionuclides will migrate with the brine by advection and diffusion through the repository, seals, the DRZ, and pores and fractures in the rock matrix.

The following subsections discuss briefly the transport of radionuclides in a number of different forms: fully dissolved, colloidal, particulate, bound to microbes, and combined with gas.

SCR.2.6.1 Solute Transport

Transport of dissolved radionuclides is accounted for in performance assessment calculations.

Solute transport may occur by advection, dispersion, and diffusion down chemical potential gradients, and is accounted for in performance assessment calculations (Sections 6.4.5.4 and 6.4.6.2.1).

SCR.2.6.2 Colloid Transport

Formation of colloids, transport of colloidal radionuclides, and colloid retardation through filtration and sorption are accounted for in performance assessment calculations.

Colloids typically have sizes of between 1 nanometer and 1 micrometer and may form stable dispersions in groundwaters. **Colloid formation and stability** depends on their composition and the prevailing chemical conditions (for example, salinity). Depending on their size, **colloid transport** may occur at different rates than those of fully dissolved species. They may be physically excluded from fine porous media, and their migration may be accelerated through fractured media in channels where velocities are greatest. However, they can also interact with the host rocks during transport and become retarded. These interactions may be of a chemical or physical nature and include electrostatic effects, leading to **colloid sorption,** and sieving leading to **colloid filtration** and pore blocking. Colloid formation and stability is accounted for in performance assessment calculations through estimates of colloid numbers in the disposal room based on the prevailing chemical conditions (Section 6.4.3.6). Colloid sorption, filtration, and transport in the Culebra are accounted for in performance assessment calculations (Section 6.4.6.2.2).

SCR.2.6.3 Particulate Transport

The formation of particulates through rinse and subsequent transport of radionuclides in groundwater and brine has been eliminated from performance assessment calculations for undisturbed conditions on the basis of low consequence to the performance of the disposal system. The transport of radionuclides as particulates (cuttings, cavings, and spallings) during penetration of the repository by a borehole, is accounted for in performance assessment calculations.

Suspensions of particles having sizes above the colloidal range are, by definition, unstable because they are subject to gravitational settling. Within the WIPP disposal rooms (the only potential source of active particulates), it is unlikely that brine flow will be rapid enough to generate (through **rinse**) and transport particulate suspensions under undisturbed conditions. Mobilization of any suspensions that may form would have the effect of a local and minor redistribution of radionuclides within the room and is unlikely, therefore, to result in significantly increased radionuclide transport from the repository. The formation of particulates through rinse and subsequent transport of radionuclides in groundwater and brine has therefore been eliminated from performance assessment calculations for undisturbed conditions on the basis of low consequence to the performance of the disposal system.

Inadvertent human intrusion into the repository by a borehole could result in transport of waste material to the ground surface through drilling-induced flow and blowouts (Section SCR.3.2.1.1.2). This waste could include material intersected by the drill bit (**cuttings**), material eroded from the borehole wall by circulating drilling fluid (**cavings**), and material that enters the borehole as the repository depressurizes (**spallings**). Transport of radionuclides by these materials and in brine is accounted for in performance assessment calculations and is discussed in Section 6.4.7.1.

SCR.2.6.4 Microbial Transport

Transport of radionuclides bound to microbes is accounted for in performance assessment calculations. The effects of biofilms on microbial transport have been eliminated from performance assessment calculations on the basis of beneficial consequence to the performance of the disposal system.

Microbes will be introduced into the disposal rooms during the operational phase of the repository and will also occur naturally in geological units throughout the disposal system. Because of their colloidal size, microbes, and any radionuclides bound to them, may be transported at different rates than radionuclides in solution. **Microbial transport** of radionuclides is accounted for in performance assessment calculations (Section 6.4.6.2.2).

Biofilms (see Section SCR.2.5.1) may influence microbial and radionuclide transport rates through their capacity to retain, and therefore retard, both the microbes themselves and radionuclides. This effect has been eliminated from performance assessment calculations on the basis of beneficial consequence to the performance of the disposal system.

SCR.2.6.5 Gas Transport

The transport of radioactive gases has been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system.

The production and potential **transport of radioactive gases** is discussed in Section SCR.2.5.1.3, where they are eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system.

SCR.2.7 Contaminant Transport Processes

SCR.2.7.1 Advection

Advection of contaminants is accounted for in performance assessment calculations.

Advection (that is, the transport of dissolved and solid material by flowing fluid) is accounted for in performance assessment calculations (Sections 6.4.5.4 and 6.4.6.2).

SCR.2.7.2 Diffusion

Diffusion of contaminants and retardation by matrix diffusion are accounted for in performance assessment calculations.

Diffusion (that is, the movement of molecules or particles both parallel to and transverse to the direction of advection in response to Brownian forces) and, more specifically **matrix diffusion**, whereby movement is transverse to the direction of advection within a fracture and into the surrounding rock matrix, are accounted for in performance assessment calculations (Section 6.4.6.2).

SCR.2.7.3 Thermochemical Transport Phenomena

The effects of thermochemical transport phenomena (the Soret effect) have been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system.

According to Fick's law, the diffusion flux of a solute is proportional to the solute gradient. In the presence of a temperature gradient there will also be a solute flux proportional to the temperature gradient (the **Soret effect**). Thus, the total solute flux **J** in a liquid phase may be expressed as

$$\mathbf{J} = - D\nabla C - ND\nabla T \ ,$$

where C is the solute concentration, T is the temperature of the liquid, D is the solute diffusion coefficient, and

$$N = S_T C(1-C) \ ,$$

in which S_T is the Soret coefficient. The mass conservation equation for solute diffusion in a liquid is then

$$\frac{\partial C}{\partial t} = \nabla \cdot (D \nabla C + N D \nabla T) \ .$$

In liquids having both light and heavy molecules, the heavier molecules tend to concentrate in the colder regions in the presence of a temperature gradient. Typically, large temperature gradients are required for Soret diffusion to be significant compared to Fickian diffusion.

Radioactive decay, nuclear criticality, and exothermic reactions are three possible sources of heat in the WIPP repository. The DOE (1980, 9-149) estimated that radioactive decay of CH-TRU waste will result in a maximum temperature rise at the center of the repository of 1.6°C at 80 years after waste emplacement (Section SCR.2.2.2). Sanchez and Trellue (1996) have shown that the total thermal load of RH-TRU waste will not significantly affect the average temperature increase in the repository. Temperature increases of about 3°C may occur at the locations of RH-TRU containers of maximum thermal power (60 watts). Such temperature increases are likely to be short-lived because of the rapid decay of heat-producing nuclides in RH-TRU waste, such as ^{137}Cs, ^{90}Sr, ^{241}Pu, and ^{147}Pm, whose half-lives are approximately 30, 29, 14, and 3 years, respectively. Soret diffusion generated by such temperature contrasts will be negligible compared to other radionuclide transport mechanisms.

Nuclear criticality is eliminated from performance assessment calculations on the basis of low probability of occurrence over 10,000 years (Section SCR.2.2.3).

Temperature increases resulting from exothermic reactions are discussed in Section SCR.2.5.7. Potentially the most significant exothermic reactions are concrete hydration, backfill hydration, and aluminum corrosion. Hydration of the seal concrete could raise the temperature of the concrete to approximately 53°C and that of the surrounding salt to approximately 38°C one week after seal emplacement (see Section SCR.2.5.7.1). However, the concrete seals will be designed to function as barriers to fluid flow for at least 100 years after emplacement, and seal permeability will be minimized (Wakeley et al. 1995). Thus, short-term temperature increases associated with concrete hydration will not result in significant Soret diffusion through the seal system.

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As discussed in Section SCR.2.5.7.2, the maximum temperature rise in the disposal panels as a consequence of backfill hydration will be less than 5°C, resulting from brine inflow following a drilling intrusion into a waste disposal panel. Note that active institutional controls will prevent drilling within the controlled area for 100 years after disposal. By this time, any heat generation by radioactive decay and concrete seal hydration will have decreased substantially, and the temperatures in the disposal panels will have reduced to close to initial values.

Under similar conditions following a drilling intrusion, aluminum corrosion could, at most, result in a short-lived (two years) temperature increase of about 6°C (see Section SCR.2.5.7.3). These calculated maximum heat generation rates resulting from aluminum corrosion and backfill hydration could not occur simultaneously because they are limited by brine availability; each calculation assumes that all available brine is consumed by the reaction of concern. Thus, the temperature rise of 6°C represents the maximum that could occur as a result of any combination of exothermic reactions occurring simultaneously. Temperature increases of this magnitude will not result in significant Soret diffusion within the disposal system.

In summary, the limited magnitude and spatial scale of temperature gradients in the disposal system indicate that Soret diffusion will be insignificant. Thus, the effects of thermochemical transport phenomena have been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system.

SCR.2.7.4 Electrochemical Transport Phenomena

The effects of electrochemical transport phenomena, comprising electrochemical reactions and electrophoresis, have been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system. The effects of galvanic coupling between the waste and metals external to the repository on transport have been eliminated from performance assessment calculations on the basis of low probability of occurrence over 10,000 years.

This section discusses electrochemical transport phenomena, including galvanic coupling, electrochemical reactions, and electrophoretic effects.

Potential gradients may exist in the subsurface as a result of groundwater flow and electrochemical reactions. The development of such potentials may be associated with the weathering of sulfide ore bodies, variations in rock properties at geological contacts, bioelectric activity associated with organic matter, natural corrosion reactions, and temperature and pressure gradients in groundwaters. With the exception of mineralization potentials associated with metallic sulfide ores (see below), the magnitude of such potentials is usually less than about 100 millivolts and the potentials tend to average to zero over distances of several thousand feet (Telford et al. 1976, 458). Temporary currents may be induced over larger distances by activity in the ionosphere, thunderstorms, and nuclear blasts. The short duration and spasmodic nature of these **electrochemical effects** is such that they have been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system.

With regard to the WIPP, **galvanic coupling** refers to the establishment of electrical potential gradients between metals in the waste form, canisters, and other metals external to the waste form. Such electrochemical effects can potentially influence corrosion processes, gas generation rates, and chemical migration. Metals other than those in the waste form and canisters can potentially include natural metallic ore bodies in the host rock and metallic elements emplaced in other parts of the repository. The absence of metallic sulfide ores in the region (Appendix GCR) allows galvanic coupling between the waste and metals external to the repository to be eliminated from performance assessment calculations on the basis of low probability of occurrences over 10,000 years.

A variety of metals will be present within the repository (for example, waste metals and metal packaging), and cells can be established over short distances. The precise interactions that may occur are complex and depend on the metals involved, their physical characteristics, and the prevailing conditions. Good physical and electrical contact between the metals involved is critical to the establishment of galvanic cells. Experiments suggest that good electrical contact is not likely to be established under repository conditions (Telander and Westerman 1993). Consequently, given the preponderance of iron over other metals within the repository and the likely passivation of many nonferrous materials, the influence of these interactions on corrosion reactions and gas generation have been eliminated from performance assessment calculations on the basis of low consequence. Because electrochemical cells that may be established are small, the effect of such cells on the migration of contaminants (for example, by **electrophoresis**) has also been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system.

SCR.2.7.5 <u>Physicochemical Transport Phenomena</u>

The effects of alpha-recoil processes on radionuclide transport have been eliminated from performance assessment calculations on the basis of low consequence to performance of the disposal system. The effects of enhanced diffusion across chemical gradients have been eliminated from performance assessments on the basis of low consequence to the performance of the disposal system. The effects of chemical gradients between material boundaries are accounted for in performance assessment calculations through the treatment of mineral fragment colloids (Section 6.4). The effects of osmotic processes have been eliminated from performance assessment calculations on the basis of beneficial consequence to the performance of the disposal system.

Physicochemical transport phenomena discussed in this section are associated with alpha-recoil and chemical gradients. These processes have the potential to influence the transport of contaminants throughout the disposal system.

SCR.2.7.5.1 <u>Alpha Recoil</u>

During decay of certain radionuclides, alpha particles may be emitted with sufficiently high energies that the daughter nuclide recoils appreciably to conserve system momentum. An example is the decay of a ^{238}U atom (originally at rest) to ^{234}Th with the emission of an alpha particle. In this case, the alpha particle is ejected with a considerable kinetic energy (approximately 4.1 megaelectron volts [6.57×10^{-13} joules]). Following the law of conservation of linear momentum, the daughter nuclide, ^{234}Th, recoils with an energy of approximately 0.07 megaelectron volts (1.12×10^{-14} joules). The potential relevance of these alpha-recoil processes to disposal system performance lies in the energy imparted to the ^{234}Th nuclide. The energy is great enough to cause the ^{234}Th nuclide to move a short distance through a crystal lattice (for example uraninite). If it is close enough to the surface of the crystal, it will be ejected into the surrounding groundwater or transferred to an adjoining solid phase.

^{234}Th decays rapidly to ^{234}Pa and subsequently to ^{234}U. The half-lives of these subsequent decay processes are 24.1 days and 1.17 minutes, respectively. Thus, in combination, these recoil and decay processes can lead to the apparent preferential dissolution or leaching of ^{234}U relative to ^{238}U from crystal structures and amorphous or adsorbed phases. This preferential leaching may also be enhanced by the radiation damage to the host phase during the emission of the alpha particle. Consequently, ^{234}U may exhibit different transport behavior than ^{238}U and contribute differently to any calculated risk.

The potential influence of **alpha-recoil** processes on radionuclide transport through natural geologic media is dependent on many site-specific factors. Among these factors are the mineralogy, geometry, and microstructure of the rocks, as well as geometrical constraints on the type of groundwater flow (for example, porous or fracture flow). Studies of natural radionuclide-bearing groundwater systems often fail to discern any measurable effect of alpha-recoil processes on radionuclide transport above the background uncertainty introduced by the spatial heterogeneity of the geological system under consideration. Consequently, the effects of the alpha-recoil processes that occur on radionuclide transport are thought to be minor. These effects have therefore been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system.

SCR.2.7.5.2 Chemical Gradients

The existence of **chemical gradients** within the disposal system, induced naturally or resulting from repository material and waste emplacement, may influence the transport of contaminants in several ways. Such gradients may exist at the interfaces between different repository materials and between repository and geological materials. For example, distinct chemical regimes are likely to be established within the concrete seals and the adjoining host rocks. Similarly, chemical gradients will exist between the waste and chemical conditioners and the surrounding rocks of the Salado. Other chemical gradients may exist as a result of the juxtaposition of relatively dilute groundwaters and brines or between groundwaters with different chemistries. Natural gradients currently exist between different groundwaters in the Culebra.

A possible consequence of chemical gradients that occur at material boundaries is the **enhanced diffusion** of materials. However, it is likely that the length scales over which such enhanced diffusion might occur will be small in comparison to the scale of the disposal system. Furthermore, a significant amount of diffusion across such interfaces will tend to reduce the driving force for migration. Therefore, the effects of enhanced diffusion across chemical gradients at material boundaries have been eliminated from performance assessments on the basis of low consequence to the performance of the disposal system.

Other processes may be induced by the existence of chemical gradients at material boundaries, including the formation or destabilization of colloids. For example, cementitious materials will be emplaced in the WIPP as part of the waste and in the seals. Cementitious materials contain colloidal-sized phases, such as calcium-silicate-hydrate gels, and alkaline pore fluids. Chemical gradients will exist between the pore fluids in the cementitious materials and their less alkaline surroundings. Chemical interactions at these interfaces may lead to the generation of colloids by chemical precipitation, and these colloids could potentially play a role in actinide transport.

The chemical conditions that will develop in the cements are such that any colloids generated from them will be of the inorganic, mineral fragment type. Candidate colloidal compositions include calcium and magnesium oxides, calcium hydroxide, calcium-aluminum silicates, calcium-silicate-hydrate gels, and silica. Experimental investigations of the stability of inorganic, mineral fragment type colloidal dispersions have been carried out as part of the WIPP colloid-facilitated actinide transport program (Papenguth and Behl 1996, 83 – 84). These investigations indicate that the salinities of the brines at WIPP are sufficient to cause kinetic destabilization of mineral fragment type colloidal dispersions. Therefore, concentrations of any colloids generated from concrete within the repository are expected to be extremely low. These concentrations are considered in performance assessment calculations.

The existence of distinct interfaces between waters of different salinities (and therefore different densities) may limit the mixing of the water bodies and affect flow and contaminant transport. Such effects have been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system.

Under appropriate circumstances, **osmotic processes** may occur at interfaces between waters of different salinities. Osmosis is the process by which water (or any other solvent) diffuses through a semipermeable (or differentially permeable) membrane in response to a concentration gradient. In geologic settings, osmotic processes can occur if waters of different salinities and/or chemistries exist on either side of a particular lithology (for example, clay) or a lithological boundary that behaves as a semipermeable membrane. At the WIPP, clay layers within the Salado may act as semipermeable membranes across which osmotic processes may occur.

In the absence of hydrological gradients across a semipermeable membrane, water will move by osmosis from the more dilute water into the more saline water. However, because of the nature of the membrane, the migration of dissolved contaminants across the interface may be restricted. The existence of a hydrological gradient across a semipermeable membrane may enhance or oppose water movement by osmosis, depending on its direction and magnitude. In cases where advection dominates over osmosis and reverse osmosis occurs, dissolved contaminants that cannot pass through the semipermeable membrane may be advected towards the membrane and concentrated along the interface. Thus, both osmosis and reverse osmosis can restrict the migration of dissolved contaminants and possibly lead to their concentration along interfaces between different water bodies. The effects of osmotic processes have been eliminated from performance assessment calculations on the basis of beneficial consequence to the performance of the disposal system.

SCR.2.8 Ecological FEPs

SCR.2.8.1 Plant, Animal, and Soil Uptake

Plant uptake, animal uptake, and accumulation in soils have been eliminated from compliance assessment calculations for 40 CFR § 191.15 on the basis of low consequence. Plant uptake and animal uptake in the accessible environment have been eliminated from performance assessment calculations for 40 CFR § 191.13 on regulatory grounds. Accumulation in soils within the controlled area has been eliminated from performance assessment calculations for 40 CFR § 191.13 on the basis of beneficial consequence.

The results of the calculations presented in Section 6.5 show that releases to the accessible environment under undisturbed conditions are restricted to lateral releases through the DRZ at repository depth. Thus, for evaluating compliance with the EPA's individual protection requirements in 40 CFR § 191.15, FEPs that relate to **plant uptake, animal uptake,** and **accumulation in soils** have been eliminated from compliance assessment calculations on the basis of low consequence.

Performance assessments for evaluating compliance with the EPA's cumulative release requirements in 40 CFR § 191.13 need not consider radionuclide migration in the accessible environment. Therefore, FEPs that relate to plant uptake and animal uptake in the accessible environment have been eliminated from performance assessment calculations on regulatory grounds. Accumulation in soils that may occur within the controlled area would reduce releases to the accessible environment and can, therefore, be eliminated from performance assessment calculations on the basis of beneficial consequence.

SCR.2.8.2 Human Uptake

Ingestion, inhalation, irradiation, dermal sorption, and injection have been eliminated from compliance assessment calculations for 40 CFR § 191.15 and Subpart C of 40 CFR Part 191 on the basis of low consequence. FEPs that relate to human uptake in the accessible environment has been eliminated from performance assessment calculations for 40 CFR § 191.13 on regulatory grounds.

As described in Section 8.1.1, releases to the accessible environment under undisturbed conditions are restricted to lateral migration through anhydrite interbeds within the Salado. Because of the bounding approach taken for evaluating compliance with the EPA's individual protection requirements in 40 CFR § 191.15 and the groundwater protection requirements in Subpart C of 40 CFR Part 191 (see Chapter 8.0, Sections 8.1.2.2 and 8.2.3), FEPs that relate to human uptake by **ingestion, inhalation, irradiation, dermal sorption,** and **injection** have been eliminated from compliance assessment calculations on the basis of low consequence.

Performance assessments for evaluating compliance with the EPA's cumulative release requirements in 40 CFR § 191.13 need not consider radionuclide migration in the accessible environment. Therefore, FEPs that relate to human uptake in the accessible environment have been eliminated from performance assessment calculations on regulatory grounds.

SCR.3 Human-Initiated EPs

The human-initiated EPs discussed in this section are relevant to the analyses conducted to determine compliance with the Containment Requirements in 40 CFR § 191.13, the Individual Protection Requirements in 40 CFR § 191.15, and the Environmental Standards for Ground Water Protection in Subpart C of 40 CFR Part 191. The DOE's consideration of human-initiated EPs draws on the criteria provided in 40 CFR Part 194 for certification of the WIPP's compliance with the 40 CFR Part 191 disposal regulations.

In Section SCR.3.1, the DOE discusses the requirements in 40 CFR Part 191 and criteria in 40 CFR Part 194 concerning the consideration of human-initiated EPs in compliance applications. In the remainder of Section SCR.3, the DOE discusses human-initiated EPs in the context of the FEP categorization scheme presented in Table SCR-3: the human-initiated EPs presented in Table SCR-3 are highlighted in the text of the screening discussions. The geology category (SCR.3.2) is concerned with human activities that could disrupt the subsurface structure. The hydrology and geochemistry category (SCR.3.3) is concerned with the potential effects of disruptive human activities on subsurface fluid flow and chemistry. The categories concerned with geomorphology (SCR.3.4), surface hydrology (SCR.3.5), climate (SCR.3.6), marine environment (SCR.3.7), and ecology (SCR.3.8) relate to potential effects on the disposal system of human-initiated EPs occurring at or near the land surface.

SCR.3.1 Regulatory Requirements

Regulatory requirements on FEPs represent FEP screening decisions made by the EPA. Thus, the logic and rationale for regulatory screening decisions are based on one or both of the following:

- Exclusion by the EPA in language that forms part of the 40 CFR Part 191 standard.

- Exclusion by the EPA in language that forms part of the 40 CFR Part 194 criteria.

Regulatory screening arguments are used largely to limit speculation concerning future, potentially disruptive, human-initiated EPs. In particular, the criterion in 40 CFR § 194.25(a), concerned with predictions of the future states of society, requires that compliance

Table SCR-3. Human-Initiated EPs and Their Screening Classifications

Events and Processes (EPs)	Screening Classification Historical/ Ongoing/ Near Future	Future	Comments	Appendix SCR Section
GEOLOGICAL EPs				SCR.3.2
Drilling			DP for boreholes that penetrate the waste and boreholes that penetrate Castile brine underlying the waste disposal region. SO-C for other future drilling.	SCR.3.2.1
Oil and gas exploration	SO-C	DP		
Potash exploration	SO-C	DP		
Water resources exploration	SO-C	SO-C		
Oil and gas exploitation	SO-C	DP		
Groundwater exploitation	SO-C	SO-C		
Archeological investigations	SO-R	SO-R		
Geothermal	SO-R	SO-R		
Other resources	SO-C	DP		
Enhanced oil and gas recovery	SO-C	DP		
Liquid waste disposal	SO-R	SO-R		
Hydrocarbon storage	SO-R	SO-R		
Deliberate drilling intrusion	SO-R	SO-R		
Excavation activities				SCR.3.2.2
Potash mining	UP	DP	UP for mining outside the controlled area. DP for mining inside the controlled area.	
Other resources	SO-C	SO-R		
Tunneling	SO-R	SO-R		
Construction of underground facilities (for example storage, disposal, accommodation)	SO-R	SO-R		
Archeological excavations	SO-C	SO-R		
Deliberate mining intrusion	SO-R	SO-R		
Subsurface explosions				SCR.3.2.3
Resource recovery				SCR.3.2.3.1
Explosions for resource recovery	SO-C	SO-R		
Underground nuclear device testing				SCR.3.2.3.2
Underground nuclear device testing	SO-C	SO-R		

Table SCR-3. Human-Initiated EPs and Their Screening Classifications (Continued)

Events and Processes (EPs)	Screening Classification Historical/ Ongoing/ Near Future	Future	Comments	Appendix SCR Section
SUBSURFACE HYDROLOGICAL AND GEOCHEMICAL EPs				SCR.3.3
Borehole fluid flow				SCR.3.3.1
Drilling-induced flow				SCR.3.3.1.1
Drilling fluid flow	SO-C	DP	DP for boreholes that penetrate the waste. SO-C for other future drilling.	
Drilling fluid loss	SO-C	DP	DP for boreholes that penetrate the waste, SO-C for other future drilling	
Blowouts	SO-C	DP	DP for boreholes that penetrate the waste and boreholes that penetrate Castile brine underlying the waste disposal region. SO-C for other future drilling.	
Drilling-induced geochemical changes	UP	DP	SO-C for units other than the Culebra.	
Fluid extraction				SCR.3.3.1.2
Oil and gas extraction	SO-C	SO-R		
Groundwater extraction	SO-C	SO-R		
Fluid injection				SCR.3.3.1.3
Liquid waste disposal	SO-C	SO-R		
Enhanced oil and gas production	SO-C	SO-R		
Hydrocarbon storage	SO-C	SO-R		
Fluid-injection induced geochemical changes	UP	SO-R	SO-C for units other than the Culebra	
Flow through abandoned boreholes			Classification distinguishes the time when drilling occurs.	SCR.3.3.1.4
Natural borehole fluid flow	SO-C	DP	DP for boreholes that penetrate Castile brine underlying the waste disposal region. SO-C for other future boreholes.	

Table SCR-3. Human-Initiated EPs and Their Screening Classifications (Continued)

Events and Processes (EPs)	Screening Classification Historical/ Ongoing/ Near Future	Future	Comments	Appendix SCR Section
Waste-induced borehole flow	SO-R	DP	DP for boreholes that penetrate the waste. SO-C for other future boreholes.	
Flow through undetected boreholes	SO-P	NA		
Borehole-induced solution and subsidence	SO-C	SO-C		
Borehole-induced mineralization	SO-C	SO-C		
Borehole-induced geochemical changes	UP	DP	SO-C for units other than the Culebra	
Excavation-induced flow			Classification distinguishes the time when excavation occurs.	SCR.3.3.2
Changes in groundwater flow due to mining	UP	DP	UP for mining outside the controlled area. DP for mining inside the controlled area.	
Changes in geochemistry due to mining	SO-C	SO-R		
Explosion-induced flow				SCR.3.3.3
Changes in groundwater flow due to explosions	SO-C	SO-R		
GEOMORPHOLOGICAL EPs				SCR.3.4
Land use and disturbances				SCR.3.4.1
Land use changes	SO-R	SO-R		
Surface disruptions	SO-C	SO-R		
SURFACE HYDROLOGICAL EPs				SCR.3.5
Water control and use				SCR.3.5.1
Damming of streams or rivers	SO-C	SO-R		
Reservoirs	SO-C	SO-R		
Irrigation	SO-C	SO-R		
Lake usage	SO-R	SO-R		
Altered soil or surface water chemistry by human activities	SO-C	SO-R		
CLIMATIC EPs				SCR.3.6
Anthropogenic climate change				SCR.3.6.1

Table SCR-3. Human-Initiated EPs and Their Screening Classifications (Continued)

Events and Processes (EPs)	Screening Classification Historical/ Ongoing/ Near Future	Screening Classification Future	Comments	Appendix SCR Section
Greenhouse gas effects	SO-R	SO-R		
Acid rain	SO-R	SO-R		
Damage to the ozone layer	SO-R	SO-R		
MARINE EPs				SCR.3.7
Marine activities				SCR.3.7.1
Coastal water use	SO-R	SO-R		
Sea water use	SO-R	SO-R		
Estuarine water use	SO-R	SO-R		
ECOLOGICAL EPs				SCR.3.8
Agricultural activities				SCR.3.8.1
Arable farming	SO-C	SO-R		
Ranching	SO-C	SO-R		
Fish farming	SO-R	SO-R		
Social and technological developments				SCR.3.8.2
Demographic change and urban development	SO-R	SO-R		
Loss of records	NA	DP		

Legend:

UP FEPs accounted for in the assessment calculations for undisturbed performance for 40 CFR § 191.13 (as well as 40 CFR § 191.15 and Subpart C of 40 CFR Part 191).

DP FEPs accounted for (in addition to all UP FEPs) in the assessment calculations for disturbed performance for 40 CFR § 191.13.

SO-R FEPs eliminated from performance assessment calculations on the basis of regulations provided in 40 CFR Part 191 and criteria provided in 40 CFR Part 194.

SO-C FEPs eliminated from performance assessment (and compliance assessment) calculations on the basis of consequence.

SO-P FEPs eliminated from performance assessment (and compliance assessment) calculations on the basis of low probability of occurrence.

assessments and performance assessments[3] "shall assume that characteristics of the future remain what they are at the time the compliance application is prepared." The scope of compliance assessments and performance assessments, with respect to the consideration of human-initiated EPs, is discussed in the following subsections.

[3] The analyses conducted to determine compliance with 40 CFR §191.15 and Subpart C of 40 CFR Part 191 are defined in 40 CFR §194.2 as "compliance assessments." "Performance assessments" (defined in 40 CFR §191.12) are required to determine compliance with the Containment Requirements in 40 CFR §191.13.

SCR.3.1.1 Scope of Compliance Assessments

Compliance assessments need only consider the undisturbed performance of the disposal system (as stated in 40 CFR § 191.15(a) and 40 CFR § 191.24(a)(1)). "Undisturbed performance" is defined in 40 CFR § 191.12 as "...the predicted behavior of a disposal system, including consideration of the uncertainties in predicted behavior, if the disposal system is not disrupted by human intrusion or the occurrence of unlikely natural events." The scope of compliance assessments is clarified further with respect to human-initiated EPs in 40 CFR § 194.54(b), which states that

> Compliance assessments of undisturbed performance shall include the effects on the disposal system of: (1) Existing boreholes in the vicinity of the disposal system, with attention to the pathways they provide for migration of radionuclides from the site; and (2) Any activities that occur in the vicinity of the disposal system prior to or soon after disposal. Such activities shall include, but shall not be limited to: Existing boreholes and the development of any existing leases that can be reasonably expected to be developed in the near future, including boreholes and leases that may be used for fluid injection activities.

The DOE assumes that "the vicinity of the disposal system" is a region outside and adjacent to the controlled area that extends far enough to include any activities that can affect the disposal system. Assessments of undisturbed performance must include consideration of human-initiated EPs relating to activities that have taken place or are reasonably expected to take place in the vicinity of the disposal system in the near future.

SCR.3.1.2 Scope of Performance Assessments

Assessments of compliance with the Containment Requirements in 40 CFR § 191.13 require consideration of "all significant processes and events," including human-initiated EPs. The scope of performance assessments is clarified with respect to human-initiated EPs in 40 CFR § 194.32. At 40 CFR § 194.32(a) the EPA states that

> Performance assessments shall consider natural processes and events, mining, deep drilling, and shallow drilling that may affect the disposal system during the regulatory time frame.

Thus, performance assessments must include consideration of human-initiated EPs relating to mining and drilling activities that might take place during the regulatory time frame. In particular, performance assessments must consider the potential effects of such activities that might take place within the controlled area at a time when institutional controls cannot be assumed to eliminate completely the possibility of human intrusion.

In implementing the Assurance Requirements (40 CFR § 191.14), the EPA has provided criteria relating to the effectiveness of institutional controls. With respect to active institutional controls, 40 CFR § 194.41(b) states that

> Performance assessments shall not consider any contributions from active institutional controls for more than 100 years after disposal.

The DOE assumes credit for active institutional controls, such that no human intrusion will take place within the controlled area for 100 years after disposal. However, consistent with 40 CFR § 194.41(b), the DOE assumes no credit in performance assessments for active institutional controls for more than 100 years after disposal.

Criteria concerning the credit that can be used for passive institutional controls in reducing the likelihood of future human intrusion are provided in 40 CFR § 194.43(c):

> The Administrator may allow the Department to assume passive institutional control credit, in the form of reduced likelihood of human intrusion, if the Department demonstrates in the compliance application that such credit is justified because the passive institutional controls are expected to endure and be understood by potential intruders for the time period approved by the Administrator. Such credit, or a smaller credit as determined by the Administrator, cannot be used for more than several hundred years and may decrease over time. In no case, however, shall passive institutional controls be assumed to eliminate the likelihood of human intrusion entirely.

The preamble to 40 CFR Part 194 clarifies that in performance assessments "the likelihood of mining may be decreased by passive institutional controls and active institutional controls, to the extent that can be justified in the compliance application and to a degree identical to that assumed for drilling." The preamble also limits any credit for passive institutional controls in deterring human intrusion to 700 years after disposal. For performance assessment calculations, passive institutional controls are assumed to be 99 percent effective for the period of time from 100 years to 700 years after disposal, as discussed in Section 6.4.12.1. Thus, the rates of future drilling and mining for the duration of this 600-year period are assumed to be 1 percent of the predicted rates of drilling and mining after 700 years.

Further criteria concerning the scope of performance assessments are provided at 40 CFR § 194.32(c):

> Performance assessments shall include an analysis of the effects on the disposal system of any activities that occur in the vicinity of the disposal system prior to disposal and are expected to occur in the vicinity of the disposal system soon after disposal. Such activities shall include, but shall not be limited to, existing boreholes and the development of any existing leases that can be reasonably expected to be developed in the near future, including boreholes and leases that may be used for fluid injection activities.

Performance assessments must include consideration of all human-initiated EPs relating to activities that have taken place or are reasonably expected to take place in the vicinity of the disposal system in the near future.

SCR.3.1.3 Categorization of Human Activities

In order to implement the criteria in 40 CFR Part 194 relating to the scope of compliance assessments and performance assessments, three categories of human activities have been defined. Distinctions are made between (1) human activities that are currently taking place and those that took place prior to the time of the compliance application, (2) human activities that might be initiated in the near future after submission of the compliance application, and (3) human activities that might be initiated after repository closure. The first two categories of EPs are considered under undisturbed performance, and EPs in the third category lead to disturbed performance conditions.

SCR.3.1.3.1 Historical, Current, and Near-Future Human Activities

Historical and current human activities include all types of resource extraction activities that have historically taken place and are currently taking place outside the controlled area. These activities are of potential significance insofar as they could affect the geological, hydrological, or geochemical characteristics of the disposal system or groundwater flow pathways outside the disposal system. Current human activities taking place within the controlled area are essentially those associated with development of the WIPP repository, which are considered in Section SCR.2. The observational data obtained as part of WIPP site characterization reflect any effects of historical and current human activities in the vicinity of the WIPP, such as groundwater extraction and oil and gas production. However, such human activities have resulted only in minor disturbances to the hydrological and geochemical conditions within the controlled area, that will have no significant effects on the long-term performance of the disposal system.

Near-future human activities include resource extraction activities that may be expected to occur outside the controlled area based on existing plans and leases. Such activities are of potential significance insofar as they could affect the geological, hydrological, or geochemical characteristics of the disposal system or groundwater flow pathways outside the disposal system. The only human activities that are expected to occur within the controlled area in the near future are those associated with development of the WIPP repository, which are considered in Section SCR.2. In order to bound the analysis of the effects of human activities outside the controlled area, the DOE assumes that any activity that is expected to be initiated in the near future, based on existing plans and leases, will be initiated prior to repository closure. Activities initiated prior to repository closure are assumed to continue until their completion, potentially at some time after disposal.

Compliance assessments (in order to satisfy the criteria in 40 CFR § 194.54(b)) and performance assessments (in order to satisfy the criteria in 40 CFR § 194.32(c)) must consider the potential effects of historical, current, and near-future human activities on the performance of the disposal system. Historical, current, and near-future human-initiated EPs and their screening classification are summarized in Table SCR-3.

SCR.3.1.3.2 Future Human Activities

Future human activities include activities that might be initiated within or outside the controlled area after repository closure. Performance assessments, but not compliance assessments, must consider the effects of future human activities on the performance of the disposal system. The EPA has provided criteria relating to future human activities in 40 CFR § 194.32(a), which limit the scope of consideration of future human activities in performance assessments to mining and drilling. Mining and drilling could occur within the disposal system at a time when institutional controls cannot be assumed to eliminate completely the possibility of such activities. Thus, mining and drilling may occur within the controlled area after the end of the period of active institutional control (100 years after disposal). Future human activities could potentially influence the transport of contaminants within and outside the disposal system, by resulting in direct removal of waste from the disposal system or alteration of the geological, hydrological, or geochemical characteristics of the disposal system. Future human-initiated EPs and their screening classification are summarized in Table SCR-3.

SCR.3.1.3.2.1 Criteria Concerning Future Mining

The EPA provides additional criteria concerning the type of future mining that should be considered by the DOE in 40 CFR § 194.32(b):

> Assessments of mining effects may be limited to changes in the hydraulic conductivity of the hydrogeologic units of the disposal system from excavation mining for natural resources. Mining shall be assumed to occur with a one in 100 probability in each century of the regulatory time frame. Performance assessments shall assume that mineral deposits of those resources, similar in quality and type to those resources currently extracted from the Delaware Basin, will be completely removed from the controlled area during the century in which such mining is randomly calculated to occur. Complete removal of such mineral resources shall be assumed to occur only once during the regulatory time frame.

Thus, consideration of future mining may be limited to mining within the disposal system at the locations of resources that are similar in quality and type to those currently extracted from the Delaware Basin.

SCR.3.1.3.2.2 Criteria Concerning Future Drilling

With respect to consideration of future drilling, in the preamble to 40 CFR Part 194, the EPA "reasoned that while the resources drilled for today may not be the same as those drilled for in the future, the present rates at which these boreholes are drilled can nonetheless provide an estimate of the future rate at which boreholes will be drilled." Criteria concerning the consideration of future deep and shallow drilling[4] in performance assessments are provided in 40 CFR § 194.33. These criteria state that, to calculate future drilling rates, the DOE should examine the historical rate of drilling for resources in the Delaware Basin. Historical drilling for purposes other than resource recovery (such as WIPP site investigation) need not be considered in determining future drilling rates.

[4] In 40 CFR §194.2, deep drilling is defined as "drilling events in the Delaware Basin that reach or exceed a depth of 2,150 feet below the surface relative to where such drilling occurs" and shallow drilling is defined as "drilling events in the Delaware Basin that do not reach a depth of 2,150 feet below the surface relative to where such drilling occurred."

In particular, in calculating the frequency of future deep drilling, 40 CFR § 194.33(b)(3)(i) states that the DOE should

> Identify deep drilling that has occurred for each resource in the Delaware Basin over the past 100 years prior to the time at which a compliance application is prepared.

and, in calculating the frequency of future shallow drilling, 40 CFR § 194.33(b)(4)(i) requires that the DOE should

> Identify shallow drilling that has occurred for each resource in the Delaware Basin over the past 100 years prior to the time at which a compliance application is prepared.

An additional criterion with respect to the calculation of future shallow drilling rates is provided in 40 CFR § 194.33(b)(4)(iii):

> In considering the historical rate of all shallow drilling, the Department may, if justified, consider only the historical rate of shallow drilling for resources of similar type and quality to those in the controlled area.

As an example of the use of the criterion in 40 CFR § 194.33(b)(4)(iii), the EPA states in the Supplementary Information to 40 CFR Part 194 that "if only non-potable water can be found within the controlled area, then the rate of drilling for water may be set equal to the historical rate of drilling for non-potable water in the Delaware Basin over the past 100 years." Thus, the DOE may estimate the rate of future shallow drilling within the controlled area based on a determination of the potential resources in the controlled area.

The EPA also provides criteria in 40 CFR § 194.33(d) concerning the use of future boreholes subsequent to drilling:

> With respect to future drilling events, performance assessments need not analyze the effects of techniques used for resource recovery subsequent to the drilling of the borehole.

Thus, performance assessments need not consider the effects of techniques used for resource extraction and recovery that would occur subsequent to the drilling of a future borehole.

The EPA provides additional criteria that limit the severity of human intrusion scenarios that must be considered in performance assessments. In 40 CFR § 194.33(b)(1), the EPA states that

> Inadvertent and intermittent intrusion by drilling for resources (other than those resources provided by the waste in the disposal system or engineered barriers designed to isolate such waste) is the most severe human intrusion scenario.

Thus, human intrusion scenarios involving intentional intrusion into the WIPP excavation, for example, to recover resources, need not be considered in performance assessments.

SCR.3.1.3.3 Summary of Regulatory Requirements

Analyses of undisturbed performance of the disposal system, included in compliance assessments and performance assessments, must consider the potential effects of historical, current, and near-future human activities. For the analyses of undisturbed performance, it is assumed that the human-initiated EPs that can be eliminated from performance assessment calculations on the basis of low probability of occurrence, low consequence, or beneficial consequence can be eliminated from compliance assessment calculations on similar bases.

Performance assessments must also include consideration of future human activities that could lead to disturbed performance conditions, although the scope of consideration of future human activities is limited to mining and drilling. In the following sections, in order to distinguish between undisturbed performance and disturbed performance, separate screening discussions and screening decisions are presented for historical, current, and near-future human-initiated EPs, and for future human-initiated EPs.

SCR.3.2 Geological EPs

The human activities discussed in this section are those that could disrupt the geology of the disposal system, or the geology in the vicinity of the disposal system, resulting in or modifying subsurface pathways for fluid flow. Drilling, excavation activities, and subsurface explosions could create interconnections between hydraulically conductive horizons, alter hydrogeological or geochemical characteristics of the disposal system, or result in direct transport of radionuclides to the accessible environment. In this section, the types of geological activities that need to be considered with regard to potential consequences are defined; the subsurface hydrological and geochemical effects of these activities are considered in Section SCR.3.3.

SCR.3.2.1 Drilling

Drilling associated with geothermal energy production, liquid waste disposal, hydrocarbon storage, archeology, and deliberate intrusion into the excavated repository, has been eliminated from performance assessment calculations on regulatory grounds. The effects of historical, current, and near-future drilling associated with water resources exploration, groundwater exploitation, potash exploration, oil and gas exploration, oil and gas exploitation, enhanced oil and gas recovery, and drilling to explore other resources, has been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system (Section SCR.3.3.1). Historical shallow drilling associated with water resources exploration, potash exploration, and groundwater exploitation, is accounted for in calculations to determine the rate of future shallow drilling. Historical deep drilling associated with oil and gas exploration, oil and gas exploitation, enhanced oil and gas recovery, potash exploration, and exploration for other resources (sulfur) is accounted for in calculations to determine the rate of future deep drilling.

This section discusses historical, current, and near-future drilling activities within and outside the controlled area and drilling activities that may take place within or outside the controlled area in the future. Drilling may occur within the controlled area in the future after the end of the period of active institutional control (100 years after disposal). Section SCR.3.3.1 discusses the potential effects on the performance of the disposal system of drilling-induced flow, postdrilling processes (fluid extraction and injection), and flow through abandoned boreholes.

SCR.3.2.1.1 Historical, Current, and Near-Future Human-Initiated EPs

Resource exploration and exploitation are the most common reasons for drilling in the Delaware Basin and are the most likely reasons for drilling in the near future. The WIPP location has been evaluated for the occurrence of natural resources in economic quantities. Powers et al. (1978) (Appendix GCR, Chapter 8) investigated the potential for exploitation of potash, hydrocarbons, caliche, gypsum, salt, uranium, sulfur, and lithium. Also, in 1995, the New Mexico Bureau of Mines and Mineral Resources (NMBMMR) performed a reevaluation of the mineral resources at and within 1 mile (1.6 kilometers) around the WIPP site.

Potash resources in the vicinity of the WIPP are discussed in Section 2.3.1.1. Throughout the Carlsbad Potash District, commercial quantities of potash are restricted to the McNutt, which forms part of the Salado above the repository horizon. **Potash exploration** and evaluation boreholes have been drilled within and outside the controlled area.

Drilling associated with **oil and gas exploration** and **oil and gas exploitation** currently takes place in the vicinity of the WIPP (see Section 2.3.1.2). For example, gas is extracted from reservoirs in the Morrow Formation, some 14,000 feet (4,200 meters) below the surface, and oil is extracted from shallower units within the Delaware Mountain Group, some 7,000 to 8,000 feet (2,150 to 2,450 meters) below the surface. Three wells were drilled for oil and gas in the controlled area prior to the LWA of 1992. One of the three wells was drilled directionally from outside the controlled area.

Secondary and tertiary oil and gas production techniques can involve the drilling of additional wells for the injection of fluid to enhance recovery. As indicated by the NMBMMR (1995), secondary production (waterflooding) is employed in the Delaware Basin, the nearest location to the WIPP site being approximately 2 miles (3 kilometers) from the outer boundary of the controlled area. Drilling associated with **enhanced oil and gas recovery** is expected to continue in the near future.

Of the **other resources** investigated by Powers et al. (1978) (Appendix GCR, Chapter 8), the extraction of caliche, gypsum, salt, and lithium is not economically viable in the vicinity of the WIPP because of the widespread occurrence of more easily accessible deposits elsewhere in the region. Uranium is not present in economic quantities near the WIPP site, and no sulfur deposits were identified in the northern Delaware Basin.

Water is currently extracted from formations above the Salado, as discussed in Section 2.3.1.3. The distribution of groundwater wells in the Delaware Basin is included in Appendix USDW (Section USDW.3). **Water resources exploration** and **groundwater exploitation** are expected to continue in the Delaware Basin.

The only other drilling that has taken place or is expected to take place in the near future within or outside the controlled area is drilling associated with WIPP site investigations, which is discussed in Section SCR.2.3.8.2. **Geothermal** energy is not considered to be a potentially exploitable resource because economically attractive geothermal conditions do not exist in the northern Delaware Basin. Oil and gas production byproducts are disposed of underground in the WIPP region, but such **liquid waste disposal** does not involve drilling of additional boreholes. **Hydrocarbon storage** takes place in the Delaware Basin, but it involves gas injection through existing boreholes into depleted reservoirs (see, for example, Burton et al. 1993, 66 – 67). **Archeological investigations** in the WIPP area have involved only minor surface disturbances and have not involved drilling (see Section 2.3.2.3).

In summary, drilling associated with water resources exploration, groundwater exploitation, potash exploration, oil and gas exploration, oil and gas exploitation, enhanced oil and gas recovery, and drilling to explore other resources has taken place and is expected to continue in the Delaware Basin. The potential effects of existing and possible near-future boreholes on fluid flow and radionuclide transport within the disposal system are discussed in Section SCR.3.3.1, where low consequence screening arguments are provided. No drilling associated with geothermal energy production, liquid waste disposal, hydrocarbon storage, and archeology has taken place in the Delaware Basin. Consistent with the future states assumptions in 40 CFR § 194.25(a), such drilling activities have been eliminated from performance assessment calculations on regulatory grounds. Also, consistent with 40 CFR § 194.33(b)(1), all near-future human-initiated EPs relating to **deliberate drilling intrusion** into the WIPP excavation have been eliminated from performance assessment calculations on regulatory grounds.

SCR.3.2.1.2 *Future Human-Initiated EPs*

Criteria in 40 CFR § 194.33 require that, to calculate the rates of future shallow and deep drilling in the Delaware Basin, the DOE should examine the historical rate of drilling for resources in the Delaware Basin.

Shallow drilling associated with water, potash, sulfur, oil, and gas extraction has taken place in the Delaware Basin over the past 100 years. However, of these resources, only water and potash are present at shallow depths (less than 2,150 feet [655 meters] below the surface) within the controlled area. Thus, consistent with 40 CFR § 194.33(b)(4), the DOE has used the historical record of shallow drilling associated with **water resources exploration**, **potash exploration**, and **groundwater exploitation**, in calculations to determine the rate of future shallow drilling in the Delaware Basin (see Appendix DEL, Section DEL.7.4).

Oil and gas are the only known resources below the repository horizon that have been exploited over the past 100 years in the Delaware Basin. However, some potash and sulfur exploration boreholes have been drilled in the Delaware Basin to depths in excess of 2,150 feet (655 meters) below the surface relative to where the drilling occurred. Thus, consistent with 40 CFR § 194.33(b)(3)(i), the DOE has used the historical record of deep drilling associated with **oil and gas exploration**, **oil and gas exploitation**, **enhanced oil and gas recovery**, **potash exploration**, and drilling associated with **other resources** (sulfur exploration), in the Delaware Basin in calculations to determine the rate of future deep drilling in the Delaware Basin (see Appendix DEL, Section DEL.7.4).

Consistent with 40 CFR § 194.33 and the future states assumptions in 40 CFR § 194.25(a), drilling for purposes other than resource recovery (such as WIPP site investigation), and drilling activities that have not taken place in the Delaware Basin over the past 100 years, need not be considered in determining future drilling rates. Thus, drilling associated with **geothermal** energy production, **liquid waste disposal**, **hydrocarbon storage**, and **archeological investigations** has been eliminated from performance assessment calculations on regulatory grounds. Furthermore, consistent with 40 CFR §194.33(b)(1), all future human-initiated EPs relating to **deliberate drilling intrusion** into the WIPP excavation have been eliminated from performance assessment calculations on regulatory grounds.

SCR.3.2.2 Excavation Activities

Tunnelling and construction of underground facilities (for example, storage, disposal, accommodation) have been eliminated from performance assessment calculations on regulatory grounds. Historical, current, and near-future mining other than for potash and archeological excavations, have been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system. Future mining other than for potash, future archeological excavations, and deliberate mining intrusion into the disposal system have been eliminated from performance assessment calculations on regulatory grounds. The effects of historical, current, near-future, and future potash mining are accounted for in performance assessment calculations (Section SCR.3.3.2).

This section discusses historical, current and expected near-future excavation activities outside the controlled area, and excavation activities that may take place within or outside the controlled area in the future. Excavation may take place within the controlled area in the future after the end of the period of active institutional control (100 years after disposal). Section SCR.3.3.2 discusses the potential effects of excavations on the performance of the disposal system.

SCR.3.2.2.1 Historical, Current, and Near-Future Human-Initiated EPs

Excavation activities that can cause underground disturbances include mining, tunnelling, construction of underground storage or disposal facilities, and archeological investigations.

Potash is the only known economically viable resource in the vicinity of the WIPP that is recovered by underground mining (see Section 2.3.1). Potash is mined extensively in the region east of Carlsbad and up to 3.1 miles (5 kilometers) from the boundaries of the controlled area. According to existing plans and leases (see Chapter 2.0, Section 2.3.1.1), **potash mining** is expected to continue in the vicinity of the WIPP in the near future. The DOE assumes that all economically recoverable potash in the vicinity of the disposal system will be extracted in the near future. Excavation for **other resources** does take place elsewhere in the Delaware Basin. In numerous areas, sand, gravel, and caliche are produced, but in all cases, these are surface quarries that are generally shallow (tens of feet).

No **construction of underground facilities (for example, storage, disposal, accommodation [that is, dwellings])** or **tunnelling** has taken place in the Delaware Basin. Gas storage does take place in the Delaware Basin, but it involves injection through boreholes into depleted reservoirs, and not excavation (see, for example, Burton et al. 1993, 66 – 67). **Archeological excavations** in the WIPP area have involved only minor surface disturbances (see Section 2.3.2.3). The only other excavation activities that have taken place in the Delaware Basin are those associated with the construction of the WIPP repository; FEPs associated with the WIPP excavation are discussed in Section SCR.2.

In summary, potash mining is currently taking place and is expected to continue in the vicinity of the WIPP in the near future. The potential effects of historical, current, and near-future potash mining are discussed in Section SCR.3.3.2, and are accounted for in performance assessment calculations. Excavation for resources other than potash and archeological excavations have taken place or are currently taking place in the Delaware Basin. These activities have not altered the geology of the controlled area significantly, and have been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system. Tunnelling and construction of underground facilities have not taken place in the Delaware Basin. Consistent with the future states assumptions in 40 CFR § 194.25(a), such excavation activities have been eliminated from performance assessment calculations on regulatory grounds. Also, consistent with 40 CFR § 194.33(b)(1), all near-future human-initiated EPs relating to **deliberate mining intrusion** into the WIPP excavation have been eliminated from performance assessment calculations on regulatory grounds.

SCR.3.2.2.2 *Future Human-Initiated EPs*

According to 40 CFR § 194.32(b), consideration of future mining may be limited to mining within the disposal system at the locations of resources that are similar in quality and type to those currently extracted from the Delaware Basin. Potash is the only resource that has been identified within the controlled area in quality similar to that currently mined elsewhere in the Delaware Basin. Future mining for **other resources** has been eliminated from performance assessment calculations on regulatory grounds. Within the controlled area, the McNutt, which forms part of the Salado above the repository horizon, provides the only potash of appropriate quality. The extent of possible future **potash mining** within the controlled area (occurring when active institutional controls are ineffective) is discussed in Section 2.3.1.1. The potential effects of future potash mining are discussed in Section SCR.3.3.2, and are accounted for in performance assessment calculations.

Consistent with the future states assumptions in 40 CFR § 194.25(a), excavation activities that have not taken place in the Delaware Basin over the past 100 years need not be included in consideration of future human activities. Thus, **tunnelling**, and **construction of underground facilities (for example, storage, disposal, accommodation)** have been eliminated from performance assessment calculations on regulatory grounds. Also, consistent with 40 CFR § 194.32(a), which limits the scope of consideration of future human actions to mining and drilling, future **archeological excavations** have been eliminated from performance assessment calculations on regulatory grounds. Furthermore, consistent with 40 CFR § 194.33(b)(1), all future human-initiated EPs relating to **deliberate mining intrusion** into the WIPP excavation have been eliminated from performance assessment calculations on regulatory grounds.

SCR.3.2.3 Subsurface Explosions

This section discusses subsurface explosions associated with **resource recovery** and **underground nuclear device testing** that may result in pathways for fluid flow between hydraulically conductive horizons. The potential effects of explosions on the hydrological characteristics of the disposal system are discussed in Section SCR.3.3.3.

SCR.3.2.3.1 Resource Recovery

Historical underground explosions for resource recovery have been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system. Future underground explosions for resource recovery have been eliminated from performance assessment calculations on regulatory grounds.

SCR.3.2.3.1.1 Historical, Current, and Near-Future Human-Initiated EPs

Neither small-scale nor regional-scale explosive techniques to enhance formation hydraulic conductivity form a part of current mainstream oil- and gas-production technology. Instead, controlled perforating and hydrofracturing are used to improve the performance of oil and gas boreholes in the Delaware Basin. However, small-scale explosions have been used in the past to fracture oil- and natural-gas-bearing units to enhance resource recovery. The size of explosion used to fracture an oil- or gas-bearing unit is limited by the need to contain the damage within the unit being exploited. In the area surrounding the WIPP, the stratigraphic units with oil and gas resources are too deep for explosions to affect the performance of the disposal system. Thus, the effects of **explosions for resource recovery** have been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system.

SCR.3.2.3.1.2 Future Human-Initiated EPs

Consistent with 40 CFR § 194.33(d), performance assessments need not analyze the effects of techniques used for resource recovery subsequent to the drilling of a future borehole. Therefore, future underground **explosions for resource recovery** have been eliminated from performance assessment calculations on regulatory grounds.

SCR.3.2.3.2 Underground Nuclear Device Testing

Historical underground nuclear device testing has been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system. Future underground nuclear device testing has been eliminated from performance assessment calculations on regulatory grounds.

SCR.3.2.3.2.1 Historical, Current, and Near-Future Human-Initiated EPs

The Delaware Basin has been used for an isolated nuclear test. This test, Project Gnome (Rawson et al. 1965, 5, 8, 35), took place in 1961 at a location approximately 8 miles (13 kilometers) southwest of the WIPP waste disposal region. Project Gnome was decommissioned in 1979.

The primary objective of Project Gnome was to study the effects of an underground nuclear explosion in salt. The Gnome experiment involved the detonation of a 3.1 kiloton nuclear device at a depth of 1,190 feet (360 meters) in the bedded salt of the Salado. The explosion created an approximately spherical cavity of about 950,000 cubic feet (27,000 cubic meters) and caused surface displacements in a radius of 1,180 feet (360 meters). No earth tremors perceptible to humans were reported at distances over 25 miles (40 kilometers) from the explosion. A zone of increased permeability was observed to extend at least 150 feet (46 meters) laterally from, and 344 feet (105 meters) above, the point of the explosion. The test had no significant effects on the geological characteristics of the WIPP disposal system. Thus, historical **underground nuclear device testing** has been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system. There are no existing plans for underground nuclear device testing in the vicinity of the WIPP in the near future.

SCR.3.2.3.2.2 Future Human-Initiated EPs

The criterion in 40 CFR § 194.32(a), relating to the scope of performance assessments, limits the consideration of future human actions to mining and drilling. Therefore, future **underground nuclear device testing** has been eliminated from performance assessment calculations on regulatory grounds.

SCR.3.3 Subsurface Hydrological and Geochemical EPs

The human-initiated EPs considered in this section relate to the potential subsurface hydrological and geochemical effects of the activities involving drilling, excavation, and subsurface explosions, discussed in Section SCR.3.2. The discussion here is limited to those human activities not eliminated from performance assessment calculations on regulatory grounds in Section SCR.3.2.

SCR.3.3.1 Borehole Fluid Flow

Borehole fluid flow during drilling, fluid extraction and injection through boreholes, and flow through abandoned boreholes could result in hydrological or geochemical disturbances of the disposal system and could affect radionuclide transport.

SCR.3.3.1.1 Drilling-Induced Flow

Drilling fluid flow, drilling fluid loss, and blowouts associated with historical, current, near-future, and future boreholes that do not intersect the waste disposal region, have been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system. The possibility of a future deep borehole penetrating a waste panel, such that drilling-induced flow results in transport of radionuclides to the land surface or to overlying hydraulically conductive units, is accounted for in performance assessment calculations. Drilling fluid loss into waste panels is accounted for in performance assessment calculations. The possibility of a deep borehole penetrating both the waste disposal region and a Castile brine reservoir is accounted for in performance assessment calculations. Geochemical changes that occur within the controlled area as a result of historical, current, near-future, and future drilling-induced flow are accounted for in performance assessment calculations.

Borehole circulation fluid could be lost to thief zones encountered during drilling, or fluid could flow from pressurized zones through the borehole to the land surface (blowout) or to a thief zone. Such drilling-related EPs could influence groundwater flow and, potentially, radionuclide transport in the affected units. Future drilling within the controlled area could result in direct releases of radionuclides to the land surface or transport of radionuclides between hydraulically conductive units.

Movement of brine from a pressurized zone, through a borehole, into potential thief zones such as the Salado interbeds or the Culebra, could result in geochemical changes and altered radionuclide migration rates in these units.

SCR.3.3.1.1.1 Historical, Current, and Near-Future Human-Initiated EPs

As discussed in Section SCR.3.2.1, drilling associated with water resources exploration, groundwater exploitation, potash exploration, oil and gas exploration, oil and gas exploitation, enhanced oil and gas recovery, and drilling to explore other resources has taken place or is currently taking place outside the controlled area in the Delaware Basin. These drilling activities are expected to continue in the vicinity of the WIPP in the near future.

Hydraulic effects of drilling-induced flow

Drilling fluid flow will not affect hydraulic conditions in the disposal system significantly unless there is substantial **drilling fluid loss** to a thief zone, such as the Culebra. Typically, zones into which significant borehole circulation fluid is lost are isolated through injection of materials to reduce permeability or through casing and cementing programs. Assuming such operations are successful, drilling fluid loss in the near future outside the controlled area will not affect the hydrology of the disposal system significantly.

Naturally occurring brine and gas pockets have been encountered during drilling in the Delaware Basin. Brine pockets have been intersected in the Castile (as discussed in Section 2.2.1.3) and in the Salado above the WIPP horizon (Section 2.2.1.2.2). Gas **blowouts** have occurred during drilling in the Salado. Usually, such events result in brief interruptions in drilling while the intersected fluid pocket is allowed to depressurize through flow to the surface (for a period lasting from a few hours to a few days). Drilling then restarts with an increased drilling mud weight. Under these conditions, blowouts in the near future will cause isolated hydraulic disturbances, but will not affect the hydrology of the disposal system significantly.

Potentially, the most significant disturbance to the disposal system could occur if an uncontrolled blowout during drilling resulted in substantial flow through the borehole from a pressurized zone to a thief zone. For example, if a borehole penetrates a brine reservoir in the Castile, brine could flow through the borehole to the Culebra, and, as a result, could affect hydraulic conditions in the Culebra. The potential effects of such an event can be compared to the effects of long-term fluid flow from deep overpressurized units to the Culebra through abandoned boreholes. Wallace (1996a) analysed the potential effects of flow through abandoned boreholes in the future within the controlled area (as discussed in Section SCR.3.3.1.4.2), and concluded that interconnections between the Culebra and deep units could be eliminated from performance assessment calculations on the basis of low consequence. Long-term flow through abandoned boreholes would have a greater hydrological impact in the Culebra than short-term drilling-induced flow outside the controlled area. Thus, the effects of fluid flow during drilling in the near future have been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system.

In summary, drilling fluid flow, drilling fluid loss, and blowouts associated with historical, current, and near-future boreholes have been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system.

Geochemical effects of drilling-induced flow

Radionuclide migration rates are governed by the coupled effects of hydrological and geochemical processes, as discussed in Sections SCR.2.6 and SCR.2.7. Human-initiated EPs outside the controlled area could affect the geochemistry of units within the controlled area if they occur sufficiently close to the edge of the controlled area. Movement of brine from a pressurized reservoir in the Castile through a borehole into potential thief zones, such as the Salado interbeds or the Culebra, could cause **drilling-induced geochemical changes** resulting in altered radionuclide migration rates in these units through their effects on colloid transport and sorption (colloid transport may enhance radionuclide migration, while radionuclide migration may be retarded by sorption).

The treatment of colloids in performance assessment calculations is described in Sections 6.4.3.6 and 6.4.6.2.2. The repository and its contents provide the main source of colloids in the disposal system. By comparison, Castile brines have relatively low total colloid concentrations. Therefore, changes in colloid transport in units within the controlled area as a result of historical, current, and near-future drilling-induced flow have been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system.

Sorption within the Culebra is accounted for in performance assessment calculations as discussed in Section 6.4.6.2. The sorption model comprises an equilibrium, sorption isotherm approximation, employing distribution coefficients (K_ds) applicable to dolomite in the Culebra (Appendix MASS, Section MASS.15.2). The CDFs of distribution coefficients used (Appendix PAR) are derived from a suite of experimental studies that include measurements of K_ds for actinides in a range of chemical systems including Culebra and Castile brines, Culebra brines, and Salado brines. Therefore, any changes in sorption geochemistry in the Culebra within the controlled area as a result of historical, current, and near-future drilling-induced flow are accounted for in performance assessment calculations.

Sorption within the Dewey Lake is accounted for in performance assessment calculations, as discussed in Section 6.4.6.6. It is assumed that the sorptive capacity of the Dewey Lake is sufficiently large to prevent any radionuclides that enter the Dewey Lake from being released over 10,000 years (Wallace et al. 1995). Sorption within other geological units of the disposal system has been eliminated from performance assessment calculations on the basis of beneficial consequence to the performance of the disposal system. The effects of changes in sorption in the Dewey Lake and other units within the controlled area as a result of historical, current, and near-future drilling-induced flow have been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system.

SCR.3.3.1.1.2 Future Human-Initiated EPs – Boreholes that Intersect the Waste Disposal Region

The consequences of drilling within the controlled area in the future will primarily depend on the location of the borehole. Potentially, future deep drilling could penetrate the waste disposal region. If the borehole intersects the waste in the disposal rooms, radionuclides could be transported as a result of **drilling fluid flow**: releases to the accessible environment may occur as material entrained in the circulating drilling fluid is brought to the surface (see Section SCR.2.6.3). Also, during drilling, contaminated brine may flow up the borehole and reach the surface, depending on fluid pressure within the waste disposal panels; **blowout** conditions could prevail if the waste panel were sufficiently pressurized at the time of intrusion. Alternatively, hydraulic and geochemical conditions in the waste panel could be affected as a result of **drilling fluid loss** to the panel and **drilling-induced geochemical changes**.

Hydraulic effects of drilling-induced flow

The possibility of a future borehole penetrating a waste panel, so that drilling fluid flow and, potentially, blowout, results in transport of radionuclides to the land surface or to overlying hydraulically conductive units, is accounted for in performance assessment calculations.

The units intersected by the borehole may provide sources for fluid flow (brine, oil, or gas) to the waste panel during drilling. In the vicinity of the WIPP, the Castile that underlies the Salado contains isolated volumes of brine at fluid pressures greater than hydrostatic. A future borehole that penetrates a Castile brine reservoir could provide a connection for brine flow from the reservoir to the waste panel, thus increasing fluid pressure and brine volume in the waste panel. The possibility of a deep borehole penetrating both a waste panel and a brine reservoir is accounted for in performance assessment calculations.

A future borehole that is drilled through a disposal room wall, but does not intersect waste, could penetrate a brine reservoir underlying the waste disposal region. Such an event would depressurize the brine reservoir to some extent, and thus would affect the consequences of any subsequent intersections of the reservoir. The possibility for a borehole to depressurize a brine reservoir underlying the waste disposal region is accounted for in performance assessment calculations.

Penetration of an underpressurized unit underlying the Salado could result in flow and radionuclide transport from the waste panel to the underlying unit during drilling, although drillers would minimize such fluid loss to a thief zone through the injection of materials to reduce permeability or through the use of casing and cementing. Also, the permeabilities of formations underlying the Salado are less than the permeability of the Culebra (Wallace 1996a). Thus, the consequences associated with radionuclide transport to an underpressurized unit below the waste panels during drilling will be less significant, in terms of disposal system performance, than the consequences associated with radionuclide transport to the land surface or to the Culebra during drilling. Through this comparison, drilling events that result in penetration of underpressurized units below the waste-disposal region have been eliminated from performance assessment calculations on the basis of beneficial consequence to the performance of the disposal system.

In evaluating the potential consequences of drilling fluid loss to a waste panel, two types of drilling events need to be considered - those that intercept pressurized fluid in underlying formations such as the Castile (defined in Section 6.3.2.2 as E1 events) and those that do not (E2 events). A possible hydrological effect would be to make a greater volume of brine available for gas generation processes and thereby increase gas volumes at particular times in the future. As discussed in Section 6.4.12.6, of boreholes that intersect a waste panel in the future, 8 percent are assumed to be E1 events and 92 percent are E2 events. For either type of drilling event, on the basis of current drilling practices, the driller is assumed to pass through the repository rapidly. Relatively small amounts of drilling fluid loss may not be noticed or may not give rise to concern. Larger fluid losses would lead to the driller injecting materials to reduce permeability, or to the borehole being cased and cemented, to limit the loss of drilling fluid.

For boreholes that intersect pressurized brine reservoirs, the volume of fluid available to flow up a borehole will be significantly greater than the volume of any drilling fluid that could be lost. This greater volume of brine is accounted for in performance assessment calculations, and is allowed to enter the disposal room (see Section 6.4.7). Thus, the effects of drilling fluid loss will be small by comparison to the potential flow of brine from pressurized brine reservoirs. Therefore, the effects of drilling fluid loss for E1 drilling events have been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system.

For boreholes that do not intersect pressurized brine reservoirs the treatment of the disposal room implicitly accounts for the potential for greater gas generation resulting from drilling fluid loss. Thus, the hydrological effects of drilling fluid loss for E2 drilling events are accounted for in performance assessment calculations within the conceptual model of the disposal room for drilling intrusions.

Geochemical effects of drilling-induced flow

Drilling fluid loss to a waste panel could modify the chemistry of disposal room brines in a manner that would affect the solubility of radionuclides and the source term available for subsequent transport from the disposal room. The majority of drilling fluids used are likely to be locally derived, and their bulk chemistry will be similar to fluids currently present in the disposal system. In addition, the presence of the MgO chemical conditioner in the disposal rooms will buffer the chemistry across a range of fluid compositions, as discussed in detail in Appendix SOTERM. Furthermore, for E1 drilling events, the volume of Castile brine that flows into the disposal room will be greater than that of any drilling fluids; Castile brine chemistry is accounted for in performance assessment calculations. Thus, the effects on radionuclide solubility of drilling fluid loss to the disposal room have been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system.

Movement of brine from a pressurized reservoir in the Castile through a borehole into thief zones, such as the Salado interbeds or the Culebra, could result in geochemical changes in the receiving units, and thus alter radionuclide migration rates in these units through their effects on colloid transport and sorption.

The repository and its contents provide the main source of colloids in the disposal system. Thus, colloid transport in the Culebra within the controlled area as a result of drilling-induced flow associated with boreholes that intersect the waste disposal region are accounted for in performance assessment calculations, as described in Sections 6.4.3.6 and 6.4.6.2.1. The Culebra is the most transmissive unit in the disposal system and it is the most likely unit through which significant radionuclide transport could occur. Therefore, colloid transport in units other than the Culebra, as a result of drilling-induced flow associated with boreholes that intersect the waste disposal region, has been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system.

As discussed in Section SCR.3.3.1.1.1, sorption within the Culebra is accounted for in performance assessment calculations. The sorption model used incorporates the effects of changes in sorption in the Culebra as a result of drilling-induced flow associated with boreholes that intersect the waste disposal region.

Consistent with the screening discussion in Section SCR.3.3.1.1.1, the effects of changes in sorption in the Dewey Lake inside the controlled area as a result of drilling-induced flow associated with boreholes that intersect the waste disposal region have been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system. Sorption within other geological units of the disposal system has been eliminated from performance assessment calculations on the basis of beneficial consequence to the performance of the disposal system.

SCR.3.3.1.1.3 Future Human-Initiated EPs – Boreholes that do not Intersect the Waste Disposal Region

Future boreholes that do not intersect the waste disposal region could nevertheless encounter contaminated material by intersecting a region into which radionuclides have migrated from the disposal panels, or could affect hydrogeological conditions within the disposal system. Consistent with the containment requirements in 40 CFR § 191.13(a), performance assessments need not evaluate the effects of the intersection of contaminated material outside the controlled area.

Movement of brine from a pressurized reservoir in the Castile, through a borehole, into thief zones such as the Salado interbeds or the Culebra, could result in **drilling-induced geochemical changes** and altered radionuclide migration rates in these units.

Hydraulic effects of drilling-induced flow

If radionuclides migrate away from the waste disposal panels through the interbeds, then deep drilling could result in the intersection of a contaminated region within the interbeds. Consequently, contaminated drill cuttings or brine could be transported to the land surface through **drilling fluid flow**. Performance assessment calculations show that lateral radionuclide migration through the Salado from the waste disposal region occurs most extensively in the undisturbed performance scenario; in this case radionuclides are transported through MB139. Based on the calculations of undisturbed performance, Economy (1996) determined the maximum quantity of radioactive material that could be transported from the waste disposal region into MB139 during the 10,000 year regulatory period. Economy (1996) calculated the normalized amount of radioactive material that enters MB139 to be approximately 0.13 EPA units; this quantity was derived using an equation similar to that used for determining normalized radionuclide releases to the accessible environment, which is presented as Equation (1) in Chapter 6.0.

The amount of contaminated material in MB139 that could be removed by drilling during the regulatory period depends primarily on the number of deep boreholes expected to be drilled in the unit area of the controlled area in 10,000 years and the cross-sectional area of these boreholes. As discussed in Appendix DEL (Section DEL.7.4), the expected rate of drilling is approximately 47 boreholes per square kilometer per 10,000 years. Based on a borehole diameter of 1.02 feet (0.311 meters), the cross-sectional area of each borehole within the Salado is approximately 0.76 square meters. Thus, in 10,000 years approximately 3.6×10^{-6} of the interbed volume will be removed from the Salado. Conservatively assuming that MB139 within the disposal system is uniformly contaminated for the entire 10,000 years with 0.13 normalized release units, then approximately 3.6×10^{-6} of the 0.13 normalized release units can be removed by drilling directly to the surface. This is approximately 5×10^{-7} normalized release units. This quantity is insignificant. Therefore, releases resulting from the intersection of contaminated material in MB139 are screened out on the basis of low consequence.

Boreholes penetrating a contaminated Culebra can also release radionuclides to the accessible environment. The maximum normalized release of radioactive material to the Culebra in 1996 performance assessment calculations is approximately 18 EPA release units. As discussed in Appendix DEL (Section DEL.7.4), approximately 69 deep and shallow boreholes per 10,000 years are assumed in performance assessment calculations. By the method presented in the previous paragraph, the maximum normalized release from the Culebra by direct drilling through a plume is on the order of 9×10^{-5}. This is insignificant. Therefore, radionuclide releases resulting from intersection of contaminated material in the Culebra have been eliminated from performance assessment calculations on the basis of low consequence.

Future boreholes could affect the hydraulic conditions in the disposal system. As discussed in Section SCR.3.3.1.1.1, intersection of pockets of pressurized gas and brine, and **drilling fluid loss**, are likely to result in short-term, isolated hydraulic disturbances, and will not affect the hydrology of the disposal system significantly. Potentially, the most significant hydraulic disturbance to the disposal system could occur if an uncontrolled **blowout** during drilling resulted in substantial flow through the borehole from a pressurized zone to a thief zone. For example, if a borehole penetrates a brine reservoir in the Castile, brine could flow through the borehole to the Culebra, and, as a result, could affect hydraulic conditions in the Culebra. The potential effects of such an event can be compared to the effects of long-term fluid flow from deep overpressurized units to the Culebra through abandoned boreholes. Wallace (1996a) analyzed the potential effects of such interconnections in the future within the controlled area (as discussed in Section SCR.3.3.1.4.2), and concluded that flow through abandoned boreholes between the Culebra and deep units could be eliminated from performance assessment calculations on the basis of low consequence. Long-term flow through abandoned boreholes would have a greater impact on Culebra hydrology than short-term drilling-induced flow within the controlled area. Thus, the effects of fluid flow during drilling in the future have been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system.

In summary, drilling fluid flow, drilling fluid loss, and blowouts associated with future boreholes that do not intersect the waste disposal region have been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system.

Geochemical effects of drilling-induced flow

Movement of brine from a pressurized reservoir in the Castile through a borehole into thief zones, such as the Salado interbeds or the Culebra, could cause geochemical changes resulting in altered radionuclide migration rates in these units through their effects on colloid transport and sorption.

The contents of the waste disposal panels provide the main source of colloids in the disposal system. Thus, consistent with the discussion in Section SCR.3.3.1.1.1, colloid transport as a result of drilling-induced flow associated with future boreholes that do not intersect the waste disposal region has been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system.

As discussed in Section SCR.3.3.1.1.1, sorption within the Culebra is accounted for in performance assessment calculations. The sorption model accounts for the effects of changes in sorption in the Culebra as a result of drilling-induced flow associated with boreholes that do not intersect the waste disposal region.

Consistent with the screening discussion in Section SCR.3.3.1.1.1, the effects of changes in sorption in the Dewey Lake within the controlled area as a result of drilling-induced flow associated with boreholes that do not intersect the waste disposal region have been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system. Sorption within other geological units of the disposal system has been eliminated from performance assessment calculations on the basis of beneficial consequence to the performance of the disposal system.

SCR.3.3.1.2 *Fluid Extraction*

Historical, current, and near-future groundwater, oil, and gas extraction outside the controlled area has been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system. Groundwater, oil, and gas extraction through future boreholes has been eliminated from performance assessment calculations on regulatory grounds.

The extraction of fluid could alter fluid-flow patterns in the target horizons, or in overlying units as a result of a failed borehole casing. Also, the removal of confined fluid from oil- or gas-bearing units can cause compaction in some geologic settings, potentially resulting in subvertical fracturing and surface subsidence.

SCR.3.3.1.2.1 Historical, Current, and Near-Future Human-Initiated EPs

As discussed in Section SCR.3.2.1, water, oil, and gas production are the only activities involving fluid extraction through boreholes that have taken place or are currently taking place in the vicinity of the WIPP. These activities are expected to continue in the vicinity of the WIPP in the near future.

Groundwater extraction outside the controlled area from formations above the Salado could affect groundwater flow. The Dewey Lake contains a productive zone of saturation south of the WIPP site. Several wells operated by the J.C. Mills Ranch south of the WIPP produce water from the Dewey Lake to supply livestock (see Section 2.2.1.4.2.1). Also, water has been extracted from the Culebra at the Engle Well approximately 6 miles south of the controlled area to provide water for livestock. No water wells in other areas in the vicinity of the WIPP are expected to be drilled in the near future because of the high concentrations of total dissolved solids in the groundwater.

If contaminated water intersects a well while it is producing, then contaminants could be pumped to the surface. Consistent with the containment requirements in 40 CFR § 191.13(a), performance assessments need not evaluate radiation doses that might result from such an event. However, compliance assessments must include any such events in dose calculations for evaluating compliance with the individual protection requirements in 40 CFR § 191.15. As discussed in Chapter 8.0, under undisturbed conditions, there are no calculated radionuclide releases to units containing producing wells.

Pumping from wells at the J.C. Mills Ranch may have resulted in reductions in hydraulic head in the Dewey Lake within southern regions of the controlled area, leading to increased hydraulic head gradients. However, these changes in the groundwater flow conditions in the Dewey Lake will have no significant effects on the performance of the disposal system, primarily because of the sorptive capacity of the Dewey Lake (see Section 6.4.6.6). Retardation of any radionuclides that enter the Dewey Lake will be such that no radionuclides will migrate through the Dewey Lake to the accessible environment within the 10,000-year regulatory period.

The effects of groundwater extraction from the Culebra from a well 6 miles south of the controlled area have been evaluated by Wallace (1996b), using an analytical solution for Darcian fluid flow in a continuous porous medium. Wallace (1996b) showed that such a well pumping at about 0.5 gallons per minute for 10,000 years will induce a hydraulic head gradient across the controlled area of about 4×10^{-5}. The hydraulic head gradient across the controlled area currently ranges from between 0.001 to 0.007. Therefore, pumping from the Engle Well will have only minor effects on the hydraulic head gradient within the controlled area even if pumping were to continue for 10,000 years. Thus, the effects of historical, current, and near-future groundwater extraction outside the controlled area have been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system.

Oil and gas extraction outside the controlled area could affect the hydrology of the disposal system. However, the horizons that act as oil and gas reservoirs are sufficiently below the repository for changes in fluid-flow patterns to be of low consequence, unless there is fluid leakage through a failed borehole casing. Also, oil and gas production horizons in the Delaware Basin are well-lithified rigid strata, so oil and gas extraction is not likely to result in compaction and subsidence (Brausch et al. 1982, 52, 61). Furthermore, the plasticity of the salt formations in the Delaware Basin will limit the extent of any fracturing caused by compaction of underlying units. Thus, neither the extraction of gas from reservoirs in the Morrow Formation (some 14,000 feet [4,200 meters] below the surface), nor extraction of oil from the shallower units within the Delaware Mountain Group (about 4,000 to 8,000 feet [1,250 to 2,450 meters] below the surface) will lead to compaction and subsidence. In summary, historical, current, and near-future oil and gas extraction outside the controlled area has been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system.

SCR.3.3.1.2.2 Future Human-Initiated EPs

Consistent with 40 CFR § 194.33(d), performance assessments need not analyze the effects of techniques used for resource recovery subsequent to the drilling of a future borehole. Therefore, **groundwater extraction** and **oil and gas extraction** through future boreholes have been eliminated from performance assessment calculations on regulatory grounds.

SCR.3.3.1.3 Fluid Injection

The hydrological effects of historical, current, and near-future fluid injection (liquid waste disposal, enhanced oil and gas production, and hydrocarbon storage) through boreholes outside the controlled area have been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system. Geochemical changes that occur inside the controlled area as a result of fluid flow associated with historical, current and near-future fluid injection are accounted for in performance assessment calculations. Liquid waste disposal, enhanced oil and gas production, and hydrocarbon storage involving future boreholes has been eliminated from performance assessment calculations on regulatory grounds.

The injection of fluids could alter fluid-flow patterns in the target horizons or, if there is accidental leakage through a borehole casing, in any other intersected hydraulically conductive zone. Injection of fluids through a leaking borehole could also result in geochemical changes and altered radionuclide migration rates in the thief units.

SCR.3.3.1.3.1 Historical, Current, and Near-Future Human-Initiated EPs

The only historical and current activities involving fluid injection through boreholes in the Delaware Basin are **enhanced oil and gas production** (waterflooding), **hydrocarbon storage** (gas reinjection), and **liquid waste disposal** (by-products from oil and gas production). These fluid injection activities are expected to continue in the vicinity of the WIPP in the near future.

Hydraulic fracturing of oil- or gas-bearing units is currently used to improve the performance of hydrocarbon reservoirs in the Delaware Basin. Fracturing is induced during a short period of high-pressure fluid injection, resulting in increased hydraulic conductivity near the borehole. Normally, this controlled fracturing is confined to the pay zone and is unlikely to affect overlying strata.

Secondary production techniques, such as waterflooding, that are used to maintain reservoir pressure and displace oil are currently employed in hydrocarbon reservoirs in the Delaware Basin (Brausch et al. 1982, 29 – 30). Reinjection of gas for storage currently takes place in a depleted gas field in the Morrow Formation of the Delaware Basin (Burton et al. 1993, 66 – 67). Similarly, disposal of liquid by-products from oil and gas production involves injection of fluid into depleted reservoirs. Such fluid injection techniques result in repressurization of the depleted target reservoir and mitigates any effects of fluid withdrawal.

The most significant effects of fluid injection would arise from substantial and uncontrolled fluid leakage through a failed borehole casing. The highly saline environment of some units can promote rapid corrosion of well casings and may result in fluid loss from boreholes.

Hydraulic effects of leakage through injection boreholes

The Vacuum field (located in the Capitan Reef, some 20 miles [30 kilometers] northeast of the WIPP site) and the Rhodes-Yates field (located in the back reef of the Capitan, some 45 miles [70 kilometers] southeast of the WIPP site) have been waterflooded for 40 years with confirmed leaking wells, which have resulted in brine entering the Salado and other formations above the Salado (see, for example, Silva 1994, 67-68). Currently, saltwater disposal takes place in the vicinity of the WIPP into formations below the Castile. However, leakages from saltwater disposal wells or waterflood wells in the near future in the vicinity of the WIPP are unlikely to occur because of the following:

- There are significant differences between the geology and lithology in the vicinity of the disposal system and that of the Vacuum and Rhodes-Yates Fields. The WIPP is located in the Delaware Basin in a fore reef environment, where a thick zone of anhydrite and halite (the Castile) exists. In the vicinity of the WIPP, oil is produced from the Brushy Canyon Formation at depths greater than 7,000 feet (2100 meters). By contrast, the Castile is not present at either the Vacuum or the Rhodes-Yates Field, which lie outside the Delaware Basin.[5] Oil production at the Vacuum Field is from the San Andres and Grayburg Formations at depths of approximately 4,500 feet (1400 meters), and oil production at the Rhodes-Yates Field is from the Yates and Seven Rivers Formations at depths of approximately 3,000 feet (900 meters). Waterflooding at the Rhodes-Yates Field involves injection into a zone only 200 feet (60 meters) below the Salado. There are more potential thief zones below the Salado near the WIPP than at the Rhodes-Yates or Vacuum Fields; the Salado in the vicinity of the WIPP is therefore less likely to receive any fluid that leaks from an injection borehole. Additionally, the oil pools in the vicinity of the WIPP are characterized by channel sands with thin net pay zones, low permeabilities, high irreducible water saturations, and high residual oil saturations. Therefore, waterflooding of oil fields in the vicinity of the WIPP on the scale of that undertaken in the Vacuum or the Rhodes-Yates Field is unlikely.

- New Mexico state regulations require the emplacement of a salt isolation casing string for all wells drilled in the potash enclave, which includes the WIPP area, to reduce the possibility of petroleum wells leaking into the Salado. Also, injection pressures are not allowed to exceed the pressure at which the rocks fracture. The injection pressure gradient must be kept below 0.2 pounds per square inch per foot (4.5×10^3 pascals per meter) above hydrostatic if fracture pressures are unknown. Such controls on fluid injection pressures limit the potential magitude of any leakages from injection boreholes.

[5] The Delaware Basin is defined in the preamble to 40 CFR Part 194 to be "those surface and subsurface formations which lie inside the innermost edge of the Capitan Reef."

- Recent improvements in well completion practices and reservoir operations management have reduced the occurrences of leakages from injection wells. For example, injection pressures during waterflooding are typically kept below about one pounds per square inch per foot (23×10^3 pascals per meter) to avoid fracture initiation. Also, wells are currently completed using cemented and perforated casing, rather than the open-hole completions used in the early Rhodes-Yates wells.

Any injection well leakages that do occur in the vicinity of the WIPP in the near future are more likely to be associated with liquid waste disposal than waterflooding. Disposal typically involves fluid injection though old and potentially corroded boreholes and does not include monitoring to the same extent as waterflooding. Such fluid injection could affect the performance of the disposal system if sufficient fluid leaked into the Salado interbeds to affect the rate of brine flow into the waste disposal panels.

Stoelzel and O'Brien (1996) evaluated the potential effects on the disposal system of leakage from a hypothetical salt water disposal borehole near the WIPP. Stoelzel and O'Brien (1996) used the two-dimensional BRAGFLO model (vertical north-south cross-section) to simulate saltwater disposal to the north and to the south of the disposal system. The disposal system model included the waste disposal region, the marker beds and anhydrite intervals near the excavation horizon, and the rock strata associated with local oil and gas developments. A worst case simulation was run using high values of borehole and anhydrite permeability and a low value of halite permeability to encourage flow to the disposal panels via the anhydrite. Also, the boreholes were assumed to be plugged immediately above the Salado (consistent with the plugging configurations described in Section 6.4.7.2). Values of key parameters for this simulation are shown in Table SCR-4.

Saltwater disposal into the Upper Bell Canyon was simulated, with annular leakage through the Salado. A total of approximately 7×10^5 cubic meters of brine was injected through the boreholes during a 50-year simulated disposal period. In this time, approximately 50 cubic meters of brine entered the anhydrite interval at the horizon of the waste disposal region. For the next 200 years the boreholes were assumed to be abandoned (with open-hole permeabilities of 1×10^{-9} square meters). Cement plugs (of permeability 10^{-17} cubic meters) were assumed to be placed at the injection interval and at the top of the Salado. Subsequently, the boreholes were prescribed the permeability of silty sand (see Section 6.4.7.2), and the simulation was continued until the end of the 10,000-year regulatory period. During this period, approximately 400 cubic meters of brine entered the waste disposal region from the anhydrite interval. This value of cumulative brine inflow is within the bounds of the values generated by performance assessment calculations for the undisturbed scenario. During the disposal well simulation, leakage from the injection boreholes is likely to have had no significant effect on the inflow rate at the waste panels.

Thus, the hydraulic effects of leakage through historical, current, and near-future boreholes outside the controlled area have been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system.

Table SCR-4. Parameters and Values Used in Screening the Effects of Water Flooding

Parameter	Value
Halite permeability	1.8×10^{-25} square meters
Anhydrite permeability	7.9×10^{-18} square meters
Effective permeability of leaking borehole	1.0×10^{-11} square meters
Injection depth	4,260 feet (1,300 meters)
Bottomhole injection pressure	3.3×10^{3} pounds per square inch (23×10^{6} pascals)
Injection pressure gradient	0.78 pounds per square inch per foot (1.8×10^{4} pascals per meter)

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Effects of density changes resulting from leakage through injection boreholes

Leakage through a failed borehole casing during a fluid injection operation in the vicinity of the WIPP could alter fluid density in the affected unit, which could result in changes in fluid flow rates and directions within the disposal system. Disposal of oil and gas production by-products through boreholes could increase fluid densities in transmissive units affected by leakage in the casing. Operations such as waterflooding use fluids derived from the target reservoir, or fluids with a similar composition, to avoid scaling and other reactions. Therefore, the effects of leakage from waterflood boreholes would be similar to leakage from disposal wells.

Denser fluids have a tendency to sink relative to less dense fluids, and, if the hydrogeological unit concerned has a dip, there will be a tendency for the dense fluid to travel in the downdip direction. If this direction is the same as the direction of the groundwater pressure gradient, there would be an increase in flow velocity, and conversely, if the downdip direction is opposed to the direction of the groundwater pressure gradient, there would be a decrease in flow velocity. In general terms, taking account of density-related flow will cause a rotation of the flow vector towards the downdip direction that is dependent on the density contrast and the dip.

Wilmot and Galson (1996) showed that brine density changes in the Culebra resulting from leakage through an injection borehole outside the controlled area will not affect fluid flow in the Culebra significantly. Potash mining activities assumed on the basis of regulatory criteria to occur in the near future outside the controlled area will have a more significant effect on modeled Culebra hydrology. The distribution of existing leases suggests that near-future mining will take place to the north, west, and south of the controlled area (see Section 2.3.1.1). The effects of such potash mining are accounted for in calculations of undisturbed performance of the disposal system (through an increase in the transmissivity of the Culebra above the mined region, as discussed in Section SCR.3.3.2). Groundwater modeling that accounts for potash mining shows a change in the fluid pressure distribution, and a consequent shift of flow directions towards the west in the Culebra within the controlled area (Wallace 1996c). A localized increase in fluid density in the Culebra resulting from leakage from an injection borehole would rotate the flow vector towards the downdip direction (towards the east).

Wilmot and Galson (1996) compared the relative magnitudes of the freshwater head gradient and the gravitational gradient and showed that the density effect is of low consequence to the performance of the disposal system. According to Darcy's Law, flow in an isotropic porous medium is governed by the gradient of fluid pressure and a gravitational term

$$\bar{v} = -\frac{k}{\mu}[\nabla p - \rho\bar{g}\ ] \ ,$$

where

$\bar{v}$	=	Darcy velocity vector	(m s^{-1})
k	=	intrinsic permeability	(m^2)
μ	=	fluid viscosity	(pa s)
∇p	=	gradient of fluid pressure	(pa m^{-1})
ρ	=	fluid density	(kg m^{-3})
$\bar{g}$	=	gravitational acceleration vector	(m s^{-2})

The relationship between the gravity-driven flow component and the pressure-driven component can be shown by expressing the velocity vector in terms of a freshwater head gradient and a density-related elevation gradient

$$\bar{v} = -K\ [\nabla H_f + \frac{\Delta\rho}{\rho_f}\nabla E\ ] \ ,$$

where

K	=	hydraulic conductivity	(m s^{-1})
∇H_f	=	gradient of freshwater head	
$\Delta\rho$	=	difference between actual fluid density and reference fluid density	(kg m^{-3})
ρ_f	=	density of freshwater	(kg m^{-3})
∇E	=	gradient of elevation	

Davies (1989, 28) defined a driving force ratio (DFR) to assess the potential significance of the density gradient

$$DFR = \frac{\Delta\rho\ |\ \nabla E\ |}{\rho_f\ |\ \nabla H_f\ |}$$

and concluded that a DFR of 0.5 can be considered an approximate threshold at which density-related gravity effects may become significant (Davies 1989, 28).

The dip of the Culebra in the vicinity of the WIPP is about 0.44° or 8 meters per kilometer to the east (Davies 1989, 42). According to Davies (1989, 47 – 48), freshwater head gradients in the Culebra between the waste panels and the southwestern and western boundaries of the accessible environment range from 4 meters per kilometer to 7 meters per kilometer, with only small changes in gradient arising from the calculated effects of near-future mining. Culebra brines have densities ranging from 1,050 to 1,100 kilograms per cubic meter (Davies 1989, 32). Assuming the density of fluid leaking from a waterflood borehole or a disposal well to be 1,215 kilograms per cubic meter (a conservative high value similar to the density of Castile brine [Popielak et al. 1983, Table C-2]), leads to a DFR of between 0.13 and 0.38. These values of the DFR show that density-related effects caused by leakage of brine into the Culebra during fluid injection operations are not significant.

In summary, the effects of historical, current, and near-future fluid injection (liquid waste disposal, enhanced oil and gas production, and hydrocarbon storage) through boreholes outside the controlled area have been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system.

Geochemical effects of leakage through injection boreholes

Injection of fluids through a leaking borehole could affect the geochemical conditions in thief zones, such as the Salado interbeds or the Culebra. Such **fluid injection-induced geochemical changes** could alter radionuclide migration rates within the disposal system in the affected units if they occur sufficiently close to the edge of the controlled area through their effects on colloid transport and sorption.

The majority of fluids injected (for example, during brine disposal) have been extracted locally during production activities. Because they have been derived locally, their compositions are similar to fluids currently present in the disposal system, and they will have low total colloid concentrations compared to those in the waste disposal panels (see Section SCR.3.3.1.1.1). The repository will remain the main source of colloids in the disposal system. Therefore, colloid transport as a result of historical, current, and near-future fluid injection has been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system.

As discussed in Section SCR.3.3.1.1.1, sorption within the Culebra is accounted for in performance assessment calculations. The sorption model used accounts for the effects of any changes in sorption in the Culebra as a result of leakage through historical, current, and near-future injection boreholes.

Consistent with the screening discussion in Section SCR.3.3.1.1.1, the effects of changes in sorption in the Dewey Lake within the controlled area as a result of leakage through historical, current, and near-future injection boreholes have been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system. Sorption within other geological units of the disposal system has been eliminated from performance assessment calculations on the basis of beneficial consequence to the performance of the disposal system.

Nonlocally derived fluids could be used during hydraulic fracturing operations. However, such fluid injection operations would be carefully controlled to minimize leakage to thief zones. Therefore, any potential geochemical effects of such leakages have been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system.

SCR.3.3.1.3.2 Future Human-Initiated EPs

Consistent with 40 CFR § 194.33(d), performance assessments need not analyze the effects of techniques used for resource recovery subsequent to the drilling of a future borehole. **Liquid waste disposal** (by-products from oil and gas production), **enhanced oil and gas production**, and **hydrocarbon storage** are techniques associated with resource recovery. Therefore, the use of future boreholes for such activities and **fluid injection-induced geochemical changes** have been eliminated from performance assessment calculations on regulatory grounds.

SCR.3.3.1.4 Flow Through Abandoned Boreholes

The effects of natural fluid flow through existing or near-future abandoned boreholes have been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system. Flow through undetected boreholes within or outside the controlled area has been eliminated from performance assessment calculations on the basis of low probability of occurrence of such boreholes. Waste-induced flow through boreholes drilled in the near future has been eliminated from performance assessment calculations on regulatory grounds. Waste-induced borehole flow and natural borehole flow through a future borehole that intersects a waste panel are accounted for in performance assessment calculations. The effects of natural borehole flow through a future borehole that does not intersect the waste-disposal region have been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system. Geochemical changes that occur inside the controlled area as a result of long-term flow associated with historical, current, near-future, and future abandoned boreholes are accounted for in performance assessment calculations. The effects of borehole-induced solution and subsidence, and mineralization, associated with existing, near-future, and future abandoned boreholes have been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system.

Abandoned boreholes could provide pathways for fluid flow and, potentially, contaminant transport between any intersected zones. For example, such boreholes could provide pathways for vertical flow between transmissive units in the Rustler, or between the Culebra and units below the Salado, which could affect fluid densities, flow rates, and flow directions.

Movement of fluids through abandoned boreholes could result in borehole-induced geochemical changes in the receiving units such as the Salado interbeds or Culebra, and thus alter radionuclide migration rates in these units.

Potentially, boreholes could provide pathways for surface-derived water or groundwater to percolate through low-permeability strata and into formations containing soluble minerals. Large-scale dissolution through this mechanism could lead to subsidence and to changes in groundwater flow patterns. Also, fluid flow between hydraulically conductive horizons through a borehole may result in changes in permeability in the affected units through mineral precipitation.

SCR.3.3.1.4.1 Historical, Current, and Near-Future Human-Initiated EPs

Abandoned water, potash, oil, and gas exploration and production boreholes exist within and outside the controlled area. The DOE assumes that records of past and present drilling activities in New Mexico are accurate and that evidence of any preexisting boreholes would be included in these records. In addition, during site selection for the WIPP, the DOE searched for evidence of boreholes and found no previously unknown holes. Even if undetected boreholes did exist, their effects on the performance of the disposal system would be insignificant, according to arguments similar to those presented below for flow through abandoned boreholes. However, **flow through undetected boreholes** within or outside the controlled area has been eliminated from performance assessment calculations on the basis of low probability of occurrence of such boreholes.

Continued resource exploration and production in the near future will result in the occurrence of many more abandoned boreholes in the vicinity of the controlled area. Institutional controls will prevent drilling (other than that associated with the WIPP development) from taking place within the controlled area in the near future. Therefore, no boreholes will intersect the waste disposal region in the near future, and **waste-induced borehole flow** in the near future has been eliminated from performance assessment calculations on regulatory grounds.

Hydraulic effects of flow through abandoned boreholes

Natural borehole flow through existing or near-future abandoned boreholes within or outside the controlled area could alter fluid pressure distributions within the disposal system.

Fluid flow and radionuclide transport within the Culebra could be affected if deep boreholes result in hydraulic connections between the Culebra and deep overpressurized or underpressurized units, or if boreholes provide interconnections for flow between shallow units. Wallace (1996a) analyzed the potential effects of interconnections between the Culebra and deep units in the future within the controlled area (as discussed in Section SCR.3.3.1.4.2) and concluded that such interconnections could be eliminated from performance assessment calculations on the basis of low consequence. Also, shallow interconnections via boreholes within the controlled area have been eliminated from performance assessment calculations on the basis of low consequence (see Section SCR.3.3.1.4.2). Long-term flow through abandoned boreholes within the controlled area would have a greater impact on Culebra hydrology than such interconnections outside the controlled area. Thus, the effects of fluid flow through existing and near-future abandoned boreholes have been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system.

Changes in fluid density resulting from flow through abandoned boreholes

Leakage from historical, current, and near-future abandoned boreholes that penetrate pressurized brine pockets in the Castile could give rise to fluid density changes in affected units. Wilmot and Galson (1996) showed that brine density changes in the Culebra resulting from leakage through an abandoned borehole would not have a significant effect on the Culebra flow field. The effects on Culebra hydrology of potash mining activities expected to occur in the near-future outside the controlled area are likely to be more significant. The effects of mining are accounted for in calculations of undisturbed performance of the disposal system (through an increase in the transmissivity of the Culebra above the mined region, as discussed in Section SCR.3.3.2). Groundwater modeling that accounts for potash mining shows a change in the fluid pressure distribution and a consequent shift of flow directions towards the west in the Culebra within the controlled area (Wallace 1996c). A localized increase in fluid density in the Culebra resulting from leakage from an abandoned borehole would rotate the flow vector towards the downdip direction (towards the east). A comparison of the relative magnitudes of the freshwater head gradient and the gravitational gradient, based on an analysis similar to that presented in Section SCR.3.3.1.3, shows that the density effect is of low consequence to the performance of the disposal system.

Geochemical effects of borehole flow

Movement of fluids through abandoned boreholes could result in **borehole-induced geochemical changes** in the receiving units such as the Salado interbeds or Culebra. Such geochemical changes could alter radionuclide migration rates within the disposal system in the affected units if they occur sufficiently close to the edge of the controlled area, or if they occur as a result of flow through existing boreholes within the controlled area through their effects on colloid transport and sorption.

The contents of the waste disposal panels provide the main source of colloids in the disposal system. Thus, consistent with the discussion in Section SCR.3.3.1.1.1, colloid transport as a result of flow through existing and near-future abandoned boreholes has been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system.

As discussed in Section SCR.3.3.1.1.1, sorption within the Culebra is accounted for in performance assessment calculations. The sorption model used accounts for the effects of changes in sorption in the Culebra as a result of flow through existing and near-future abandoned boreholes.

Consistent with the screening discussion in Section SCR.3.3.1.1.1, the effects of changes in sorption in the Dewey Lake inside the controlled area as a result of flow through existing and near-future abandoned boreholes have been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system. Sorption within other geological units of the disposal system has been eliminated from performance assessment calculations on the basis of beneficial consequence to the performance of the disposal system.

Borehole-induced solution and subsidence

Three features are required for significant **borehole-induced solution and subsidence** to occur through downward percolation of freshwater: a borehole, an energy gradient to drive freshwater downward through underlying brines to the Salado, and a sink or conduit to allow migration of brine away from the site of dissolution. Without these features, minor dissolution in the immediate vicinity of a borehole could occur, but percolating water would become saturated and prevent further dissolution.

An example of borehole-induced dissolution and subsidence occurred about 100 miles (160 kilometers) southeast of the WIPP site (outside the Delaware Basin) at the Wink Sink (Johnson 1987); percolation of shallow groundwater through abandoned boreholes, dissolution of the Salado, and subsidence of overlying units led to a surface collapse feature 360 feet (110 meters) in width and 110 feet (34 meters) deep. At Wink Sink, the Salado is underlain by the Tansill, Yates, and Capitan Formations, which contain vugs and solution cavities through which brine could migrate. Also, the hydraulic head of the Santa Rosa (the uppermost aquifer) is greater than those of the deep aquifers (Tansill, Yates, and Capitan Formations), suggesting downward flow if a connection were established.

The size of the dissolution cavity that caused Wink Sink is not known, but the size of the surface hollow suggests that, of existing boreholes that penetrate below repository depth near the WIPP, only ERDA-9 (see Chapter 2.0, Figure 2-2) is close enough to the repository to be of concern. Sealing of WIPP investigation boreholes (discussed in Chapter 3.0) and plugging of oil and gas boreholes (see Appendix DEL) will, to some extent, reduce the potential for borehole-induced solution and subsidence. However, corrosion of the well casing over the long term could allow percolation of surface-derived and shallow-formation waters into the borehole. Even if extensive seals are emplaced, casing corrosion could still allow a flow path to develop in strata where salt creep is not active. However, the bottom of ERDA-9 is in the Castile, just below the Salado. No sink exists at such a depth for downward percolation of water to persist.

Beauheim (1986) considered the direction of natural fluid flow through boreholes in the vicinity of the WIPP. Beauheim (1986, 72) examined hydraulic heads measured using drill stem tests in the Bell Canyon and the Culebra at well DOE-2 and concluded that the direction of flow in a cased borehole open only to the Bell Canyon and the Culebra would be upward. However, dissolution of halite in the Castile and the Salado would increase the relative density of the fluid in an open borehole, causing a reduction in the rate of upward flow. Potentially, the direction of borehole fluid flow could reverse, but such a flow could be sustained only if sufficient driving pressure, porosity, and permeability exist for fluid to flow laterally within the Bell Canyon. A further potential sink for Salado-derived brine is the Capitan Limestone. However, the subsurface extent of the Capitan Reef is approximately 10 miles (16 kilometers) from the WIPP at its closest point, and this unit will not provide a sink for brine derived from boreholes in the vicinity of the controlled area. A similar screening argument is made for natural deep dissolution in the vicinity of the WIPP (see Section SCR.1.1.5.1.). Thus, the effects of borehole-induced solution and subsidence around existing abandoned boreholes, and boreholes drilled and abandoned in the near-future, have been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system.

Borehole-induced mineralization

Fluid flow between hydraulically conductive horizons through a borehole may result in changes in permeability in the affected units through mineral precipitation. For example:

- Limited calcite precipitation may occur as the waters mix in the Culebra immediately surrounding the borehole, and calcite dissolution may occur as the brines migrate away from the borehole due to variations in water chemistry along the flow path.

- Gypsum may be dissolved as the waters mix in the Culebra immediately surrounding the borehole but may precipitate as the waters migrate through the Culebra.

The effects of these mass transfer processes on groundwater flow depend on the original permeability structure of the Culebra rocks and the location of the mass transfer. The volumes of minerals that may precipitate and/or dissolve in the Culebra as a result of the injection of Castile or Salado brine through a borehole will not affect the existing spatial variability in the permeability field significantly. Consequently, the effects of **borehole-induced mineralization** on permeability and groundwater flow within the Culebra, as a result of brines introduced via any existing abandoned boreholes, and boreholes drilled and abandoned in the near-future, have been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system.

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SCR.3.3.1.4.2 Future Human-Initiated EPs

The EPA provides criteria concerning analysis of the consequences of future drilling events in 40 CFR § 194.33(c). Consistent with these criteria, the DOE assumes that after drilling is complete the borehole is plugged according to current practice in the Delaware Basin (see Section 6.4.7.2). Degradation of casing and/or plugs may result in connections for fluid flow and, potentially, contaminant transport between connected hydraulically conductive zones. The long-term consequences of boreholes drilled and abandoned in the future will primarily depend on the location of the borehole and the borehole casing and plugging methods used.

Hydraulic effects of flow through abandoned boreholes

An abandoned future borehole that intersects a waste panel could provide a connection for contaminant transport away from the repository horizon. If the borehole has degraded casing and/or plugs, and the fluid pressure within the waste panel is sufficient, radionuclides could be transported to the land surface. Additionally, if brine flows through the borehole to overlying units, such as the Culebra, it may carry dissolved and colloidal actinides that can be transported laterally to the accessible environment by natural groundwater flow in the overlying units. Long-term **waste-induced borehole flow** is accounted for in performance assessment calculations (see Section 6.4.7.2).

The units intersected by a future borehole that intersects a waste panel may provide sources or sinks for long-term fluid flow to or from the waste panel. For example, penetration of an underpressurized unit underlying the Salado could result in long-term downward flow and radionuclide transport from the waste panel to the underlying unit. The permeabilities of formations underlying the Salado are less than the permeability of the Culebra (Wallace 1996a). Thus, under similar driving forces, fluids would migrate more rapidly through the Culebra than through units underlying the Salado. The consequences associated with radionuclide transport to an underpressurized unit below the waste panels are likely to be less significant, in terms of disposal system performance, than the consequences associated with radionuclide transport to the land surface or to the Culebra. Through this comparison, radionuclide transport to underpressurized units below the waste-disposal region has been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system.

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A future borehole that penetrates a Castile brine reservoir could provide a connection for brine flow from the reservoir to the waste panel, thus increasing fluid pressure and brine volume in the waste panel. Long-term **natural borehole flow** through such a borehole is accounted for in performance assessment calculations (see Section 6.4.8).

Deep abandoned boreholes that intersect the Salado interbeds near the waste disposal panels could provide pathways for long-term radionuclide transport from the waste panels to the land surface or to overlying units. The potential significance of such events were assessed by WIPP Performance Assessment Division (1991, B-26 to B-27), which examined single-phase flow and transport between the waste panels and a borehole intersecting MB139 outside the DRZ. The analysis assumed an in situ pressure of 11 megapascals in MB139, a borehole pressure of 6.5 megapascals (hydrostatic) at MB139, and a constant pressure of 18 megapascals as a source term in the waste panels representing gas generation. Also, MB139 was assigned a permeability of approximately 3×10^{-20} square meters and a porosity of 0.01 percent. The disturbed zone was assumed to exist in MB139 directly beneath the repository only and was assigned a permeability of 1.0×10^{-17} square meters and a porosity of 0.055 percent. Results showed that the rate of flow through a borehole located just 0.25 meters outside the DRZ would be more than two orders of magnitude less than the rate of flow through a borehole located within the DRZ because of the contrast in permeability. Thus, any releases of radionuclides to the accessible environment through deep boreholes that do not intersect waste panels would be insignificant compared to the releases that would result from transport through boreholes that intersect waste panels. Thus, radionuclide transport through deep boreholes that do not intersect waste panels has been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system.

Fluid flow and radionuclide transport within the Culebra could be affected if future deep boreholes result in hydraulic connections between the Culebra and deep overpressurized or underpressurized units. Over the 10,000-year regulatory period, a large number of deep boreholes could be drilled within and around the controlled area (see Section 6.4.12.2). The effects on the performance of the disposal system of long-term hydraulic connections between the Culebra and deep units depends on the location of the boreholes. In some cases, changes in the Culebra flow field caused by interconnections with deep units could increase lateral radionuclide travel times to the accessible environment.

As part of an analysis to determine the impact of such interconnections, Wallace (1996a) gathered information on the pressures, permeabilities, and thicknesses of potential oil- or gas-bearing sedimentary units; such units exist to a depth of about 18,000 feet (5,500 meters) in the vicinity of the WIPP. Of these units, the Atoka Unit, some 13,100 feet (4,000 meters) below the land surface, has the highest documented pressure of about 9,300 pounds per square inch (64×10^6 pascals), with permeabilities of about 2×10^{-14} square meters. The Strawn Unit, 12,800 feet (3,900 meters) below the land surface, has the lowest pressures (5,000 pounds per square inch [35×10^6 pascals], which is lower than hydrostatic) and highest permeability (10^{-13} square meters) of the deep units. Thus, in order to assess the maximum potential impact of interconnections between deep units and the Culebra, Wallace (1996a) evaluated the effects of long-term flow through boreholes from the Atoka to the Culebra (source) and from the Culebra to the Strawn (sink). Although the Atoka is primarily a gas-bearing unit, Wallace (1996a) conservatively assumed that the unit is brine saturated; in the long term, gas from the Atoka would most likely flow through a borehole to the land surface and would not affect the Culebra significantly.

Performance assessment calculations indicate that the shortest radionuclide travel times to the accessible environment through the Culebra occur when flow in the Culebra in the disposal system is from north to south. Wallace (1996a) ran the steady-state SECOFL2D model with the performance assessment data that generated the shortest radionuclide travel times (with and without mining in the controlled area) but perturbed the flow field by placing a brine source borehole in the Culebra just north of the waste disposal panels and a sink borehole just south of the controlled area. The fluid flux through each borehole was determined using Darcy's Law, assuming a borehole hydraulic conductivity of 10^{-4} meter per second (for a permeability of about 10^{-11} square meters), a borehole radius of 0.8 feet (0.25 meters), and a fluid pressure in the Culebra of 1,790 pounds per square inch (12.3×10^{6} pascals) at a depth of about 650 feet (200 meters). Thus, the Atoka was assumed to transmit brine to the Culebra at about 1.4×10^{-5} cubic meters per second, and the Strawn was assumed to receive brine from the Culebra at about 1.5×10^{-6} cubic meters per second.

Travel times through the Culebra to the accessible environment were calculated using the SECOFL2D velocity fields for particles released to the Culebra above the waste panels, assuming no retardation by sorption or diffusion into the rock matrix. Mean Darcy velocities were then determined from the distance each radionuclide travelled, the time taken to reach the accessible environment, and the effective Culebra porosity. The results show that, at worst, interconnections between the Culebra and deep units could cause a doubling of the largest mean Darcy velocity expected in the Culebra in the absence of such interconnections.

Performance assessment calculations show that radionuclide retardation in the Culebra limits lateral migration of radionuclides to just a few hundred meters in the 10,000-year regulatory time frame. A doubling of the Darcy velocity would cause only a minor increase in the lateral extent of radionuclide migration through the Culebra and would not lead to any radionuclide releases to the accessible environment in the regulatory time frame. Thus, the effects of fluid flow through a future deep abandoned borehole that does not intersect the waste disposal region have been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system.

Future abandoned boreholes could also provide interconnections for long-term fluid flow between shallow units (overlying the Salado). In particular, abandoned boreholes could provide pathways for downward flow of water from the Magenta to the Culebra; the Culebra hydraulic head is lower than the Tamarisk hydraulic head and these units are hydraulically isolated from each other by the relatively low permeability Tamarisk. If a large number of such boreholes were to occur in and around the controlled area in the future, they could result in an effective increase in vertical hydraulic conductivity in the Tamarisk. On the basis of three-dimensional groundwater flow modeling, Corbet (1995) determined that an increase in vertical hydraulic conductivity in the Tamarisk would result in a reduction in hydraulic head in the Magenta and an increase in hydraulic head in the Culebra, although there would be little change in the magnitude of the horizontal hydraulic head gradient in the Culebra. However, the change in the Culebra hydraulic head would be accompanied by a change in flow direction from north-south to northeast-southwest within the controlled area. Culebra hydraulic conductivities to the southwest of the waste panel region are two to three orders of magnitude lower than those to the south of the waste panel region. Therefore, the change in flow direction in the Culebra induced by connections to the Magenta would increase radionuclide travel times laterally through the Culebra to the accessible environment. Note that the Culebra hydraulic head would remain lower than the land surface and, therefore, radionuclides could not be transported vertically through boreholes to the accessible environment. Thus, a large number of future borehole interconnections between shallow units would be beneficial to the long-term performance of the disposal system.

The most likely conditions under which radionuclide travel times through the Culebra might decrease are those in which a specific configuration of boreholes caused the hydraulic head gradient in the Culebra to increase without changing the flow direction. This might be achieved if one or more future abandoned boreholes were to exist just north of the waste disposal region, providing a pathway for flow from the Magenta to the Culebra. The Culebra hydraulic head would be raised at this point. The increase in hydraulic head gradient caused by such an event would be less than that caused by long-term flow from a deep overpressurized unit such as the Atoka. As discussed above, flow to the Culebra from deep overpressurized units will be of low consequence to the performance of the disposal system. Thus, by comparison, the effects of a connection via a borehole between the Magenta and the Culebra have been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system.

Changes in fluid density resulting from flow through abandoned boreholes

A future borehole that intersects a pressurized brine reservoir in the Castile could also provide a source for brine flow to the Culebra in the event of borehole casing leakage, with a consequent localized increase in fluid density in the Culebra. The effect of such a change in fluid density would be to increase any gravity-driven component of groundwater flow. If the downdip direction, along which the gravity-driven component would be directed, is different to the direction of the groundwater pressure gradient, there would be a rotation of the flow vector towards the downdip direction. The groundwater modeling presented by Davies (1989, 50) indicates that a borehole that intersects a pressurized brine pocket and causes a localized increase in fluid density in the Culebra above the waste panels would result in a rotation of the flow vector slightly towards the east. However, the magnitude of this effect would be small in comparison to the effects of the head gradient (see Section SCR.3.3.1.3), and such a localized increase in density would not divert radionuclides into the high-transmissivity zone within the Culebra.

Over the 10,000-year regulatory period a large number of boreholes could be drilled within and around the controlled area (see Section 6.4.12.2). If sufficient of these boreholes intersect pressurized brine pockets and connect with the Culebra, density changes in the Culebra may become widespread.

Gravity effects related to increase in density of Culebra groundwaters south of the waste panels will be small in comparison to freshwater head gradients (see Section SCR.3.3.1.3). The calculations undertaken by Davies (1989, 50) show that a density increase in the northern part of the controlled area could rotate the flow vector and hence affect flow in the region of the waste panels. However, these calculations did not consider any effects of mining on flow in the Culebra, and were based on a relatively flat pressure gradient in this region. Accounting for potash mining (through an increase in the transmissivity of the Culebra above the mined region) results in a rotation of the freshwater head gradient towards the west (see Wallace, 1996c). Density-related gravity effects would oppose this gradient and increase travel times to the western boundary of the controlled area.

Geochemical effects of flow through abandoned boreholes

Movement of fluids through abandoned boreholes could result in **borehole-induced geochemical changes** in the receiving units, such as the Salado interbeds or Culebra. Such geochemical changes could alter radionuclide migration rates within the disposal system in the affected units through their effects on colloid transport and sorption.

The waste disposal panels provide the main source of colloids in the disposal system. Colloid transport within the Culebra as a result of long-term flow associated with future abandoned boreholes that intersect the waste disposal region are accounted for in performance assessment calculations, as described in Sections 6.4.3.6 and 6.4.6.2.1. Consistent with the discussion in Section SCR.3.3.1.1.1, colloid transport as a result of flow through future abandoned boreholes that do not intersect the waste disposal region has been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system. The Culebra is the most transmissive unit in the disposal system and it is the most likely unit through which significant radionuclide transport could occur. Therefore, colloid transport in units other than the Culebra, as a result of flow through future abandoned boreholes, has been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system.

As discussed in Section SCR.3.3.1.1.1, sorption within the Culebra is accounted for in performance assessment calculations. The sorption model accounts for the effects of changes in sorption in the Culebra as a result of flow through future abandoned boreholes.

Consistent with the screening discussion in Section SCR.3.3.1.1.1, the effects of changes in sorption in the Dewey Lake within the controlled area as a result of flow through future abandoned boreholes have been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system. Sorption within other geological units of the disposal system has been eliminated from performance assessment calculations on the basis of beneficial consequence to the performance of the disposal system.

Borehole-induced solution and subsidence

The only conditions under which significant dissolution around future boreholes might occur are those in which such a borehole intersects the WIPP excavation. Following corrosion of the steel borehole casing and degradation of the borehole plug immediately above the Salado (see Section 6.4.7.2), the excavated region could provide a sink for downward flow of water from units overlying the Salado, resulting in dissolution of the borehole wall. Downward flow could only occur prior to the occurrence of significant gas generation, brine inflow, or creep closure in the disposal rooms, when the fluid pressure is less than hydrostatic pressure.

Dissolution will continue until fluid pressures in the disposal room reach hydrostatic and downward flow ceases.

Maximum dissolution, and maximum increase in borehole diameter, will occur at the top of the Salado; dissolution will decrease with depth as the percolating water becomes salt saturated. Eventually, degraded casing and concrete plug products, clays, and other materials will fill the borehole. Long-term flow through a borehole that intersects a waste panel is accounted for in disturbed performance calculations by assuming that the borehole is eventually filled by such materials, which have the properties of a silty sand (see Section 6.4.7.2). However, these calculations assume that the borehole diameter does not increase with time.

The potential extent of enlargement of a borehole that intersects a waste panel can be assessed given flow rates through the borehole and an estimate of the salt dissolution rate. The performance assessment calculations for an E2 drilling event at 1,000 years show a mean value of approximately 2×10^5 cubic feet (5×10^3 cubic meters) of fluid flowing into the intersected waste panel through the borehole up to the end of the 10,000-year regulatory period. Assuming instantaneous dissolution of salt upon contact with freshwater, Christensen et al. (1983, 19) estimated that 0.2 cubic feet of salt are dissolved for every cubic foot of freshwater that flows through a borehole. Thus, if 2×10^5 cubic feet (5×10^3 cubic meters) of water flow through the borehole, then approximately 4×10^4 cubic feet (1×10^3 cubic meters) of salt around the borehole will be dissolved.

The dimensions of a cavity resulting from borehole-induced dissolution can be estimated by assuming that the aspect ratio of such a cavity would be similar to the aspect ratio of the surface subsidence caused by dissolution at Wink Sink. The aspect ratio (depth and width) of the surface collapse at Wink Sink is 0.3 (see Section SCR.3.3.1.4.1). Assuming that the borehole-induced dissolution cavity is conical in shape, then a dissolution cavity of volume 4×10^4 cubic feet (1×10^3 cubic meters) will have a depth of approximately 20 feet (6 meters) and a diameter of approximately 65 feet (20 meters). The salt between the waste panel and the top of the Salado is approximately 1,250 feet (380 meters) thick. Thus, such dissolution will not affect the integrity of the majority of the salt above the waste panels, and it is unlikely to affect the rate of fluid flow through the borehole to the waste panel. The subsidence induced by such a cavity could result in an increase in hydraulic conductivity within the Culebra though increased vertical strain accompanied by fracture opening. However, the change in hydraulic conductivity within the Culebra from borehole-induced solution and subsidence will be restricted to the area above the waste panels, and will have no significant affect on the long-term performance of the disposal system.

In summary, the effects of **borehole-induced solution and subsidence** around future abandoned boreholes have been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system.

Borehole-induced mineralization

Fluid flow between hydraulically conductive horizons through a future borehole may result in changes in permeability in the affected units through mineral precipitation. However, the effects of mineral precipitation as a result of flow through a future borehole in the controlled area will be similar to the effects of mineral precipitation as a result of flow through an existing or near-future borehole (see Section SCR.3.3.1.4.1). Thus, **borehole-induced mineralization** associated with flow through a future borehole has been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system.

SCR.3.3.2 Excavation-Induced Flow

Changes in groundwater flow due to historical, current, near-future, and future potash mining are accounted for in performance assessment calculations. Changes in geochemistry due to historical, current, and near-future potash mining have been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system. Changes in geochemistry due to future mining have been eliminated from performance assessment calculations on regulatory grounds.

Excavation activities may result in hydrological disturbances of the disposal system. Subsidence associated with excavations may affect groundwater flow patterns through increased hydraulic conductivity within and between units. Fluid flow associated with excavation activities may also result in changes in brine density and geochemistry in the disposal system.

SCR.3.3.2.1 Historical, Current, and Near-Future Human-Initiated EPs

As discussed in Section SCR.3.2.2, potash mining is the only excavation activity currently taking place in the vicinity of the WIPP that could affect hydrogeological or geochemical conditions in the disposal system. Potash is mined in the region east of Carlsbad and up to 3.1 miles (5 kilometers) from the boundaries of the controlled area. Mining of the McNutt in the Salado is expected to continue in the vicinity of the WIPP (see Section 2.3.1.1): the DOE assumes that all economically recoverable potash in the vicinity of the WIPP (outside the controlled area) will be extracted in the near future.

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Hydrogeological effects of mining

Potash mining in the Delaware Basin typically involves constructing vertical shafts to the elevation of the ore zone and then extracting the minerals in an excavation that follows the trend of the ore body. Potash has been extracted using conventional room and pillar mining, secondary mining where pillars are removed, and modified long-wall mining methods. Mining techniques used include drilling and blasting (used for mining langbeinite) and continuous mining (commonly used for mining sylvite). The DOE (Westinghouse 1994, 2-17 to 2-19) reported investigations of subsidence associated with potash mining operations located near the WIPP. The reported maximum total subsidence at potash mines is about 5 feet (1.5 meters), representing up to 66 percent of initial excavation height, with an observed angle of draw from the vertical at the edge of the excavation of 58 degrees. The DOE (Westinghouse 1994, 2-22 to 2-23) found no evidence that subsidence over local potash mines had caused fracturing sufficient to connect the mining horizon to water-bearing units or the surface. However, subsidence associated with mining in the McNutt in the vicinity of the WIPP may affect the lateral hydraulic conductivity of overlying units, such as the Culebra, which could influence the direction and magnitude of fluid flow within the disposal system. Such **changes in groundwater flow due to mining** are accounted for in calculations of undisturbed performance of the disposal system (see Section 6.4.6.2.3).

Potash mining, and the associated processing outside the controlled area, have changed fluid densities within the Culebra, as demonstrated by the areas of higher densities around boreholes WIPP-27 and WIPP-29 (Davies 1989, 43). Transient groundwater flow calculations (Davies 1989, 77 – 81) show that brine density variations to the west of the WIPP site caused by historical and current potash processing operations will not persist because the rate of groundwater flow in this area is fast enough to flush the high density groundwaters to the Pecos River. These calculations also show that accounting for the existing brine density variations in the region east of the WIPP site, where hydraulic conductivities are low, would have little effect on the direction or rate of groundwater flow. Therefore, changes in fluid densities from historical and current human-initiated EPs have been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system.

The distribution of existing leases and potash grades suggests that near-future mining will take place to the north, west, and south of the controlled area (see Appendix DEL). Groundwater modeling that accounts for mining (through an increase in the transmissivity of the Culebra above the mined region) shows a change in the fluid pressure distribution, and a consequent shift of flow directions towards the west in the Culebra within the controlled area (Wallace, 1996c). A localized increase in fluid density in the Culebra, in the mined region or elsewhere outside the controlled area, would rotate the flow vector towards the downdip direction (towards the east). A comparison of the relative magnitudes of the freshwater head gradient and the gravitational gradient (based on an analysis identical to that presented for fluid leakage to the Culebra through boreholes) shows that the density effect is of low consequence to the performance of the disposal system.

Geochemical effects of mining

Fluid flow associated with excavation activities may result in geochemical disturbances of the disposal system. Some waters from the Culebra reflect the influence of current potash mining, having elevated potassium to sodium ratios. However, potash mining has had no significant effect on the geochemical characteristics of the disposal system. Solution mining, which involves the injection of freshwater to dissolve the ore body, can be used for extracting sylvite. However, lack of availability of freshwater has resulted in limited use of this mining technique in the Delaware Basin, and solution mining is not expected to occur in the near future in the vicinity of the WIPP site. Thus, **changes in geochemistry due to mining** (historical, current, and near-future) have been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system.

SCR.3.3.2.2 Future Human-Initiated EPs

Consistent with 40 CFR § 194.32(b), consideration of future mining may be limited to potash mining within the disposal system (see Section 3.3.2). Within the controlled area, the McNutt provides the only potash of appropriate quality. The extent of possible future potash mining within the controlled area is discussed in Section 2.3.1.1. Criteria concerning the consequence modeling of future mining are provided in 40 CFR § 194.32(b): the effects of future mining may be limited to changes in the hydraulic conductivity of the hydrogeologic units of the disposal system. Thus, consistent with 40 CFR § 194.32(b), **changes in groundwater flow due to mining** within the controlled area are accounted for in calculations of the disturbed performance of the disposal system (see Section 6.4.6.2.3). Other potential effects, such as **changes in geochemistry due to mining**, have been eliminated from performance assessment calculations on regulatory grounds.

SCR.3.3.3 Explosion-Induced Flow

Changes in groundwater flow due to historical explosions have been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system. Changes in groundwater flow due to future explosions have been eliminated from performance assessment calculations on regulatory grounds.

This section discusses the potential hydrological disturbances of the disposal system that may occur as a result of explosions.

SCR.3.3.3.1 Historical, Current, and Near-Future Human-Initiated EPs

The small-scale explosions that have been used in the Delaware Basin to fracture oil- and natural-gas-bearing units to enhance resource recovery have been too deep to have disturbed the hydrology of the disposal system (see Section SCR.3.2.3.1).

Also, as discussed in Section SCR.3.2.3.2, the Delaware Basin has been used for an isolated nuclear test (Project Gnome), approximately 8 miles (13 kilometers) southwest of the WIPP waste disposal region. An induced zone of increased permeability was observed to extend 150 feet (46 meters) laterally from the point of the explosion. The increase in permeability was primarily associated with motions and separations along bedding planes, the major pre-existing weaknesses in the rock. This region of increased permeability is too far from the WIPP site to have had a significant effect on the hydrological characteristics of the disposal system. Thus, **changes in groundwater flow due to explosions** in the past have been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system.

SCR.3.3.3.2 Future Human-Initiated EPs

The criterion in 40 CFR § 194.32(a), relating to the scope of performance assessments, limits the consideration of future human actions to mining and drilling. Also, consistent with 40 CFR § 194.33(d), performance assessments need not analyze the effects of techniques used for resource recovery subsequent to the drilling of a future borehole. Therefore, **changes in groundwater flow due to explosions** in the future have been eliminated from performance assessment calculations on regulatory grounds.

SCR.3.4 Geomorphological EPs

SCR.3.4.1 Land Use and Disturbances

The effects of historical, current, and near-future surface disruptions have been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system. The effects of future surface disruptions have been eliminated from performance assessment calculations on regulatory grounds. Land use changes have been eliminated from performance assessment calculations on regulatory grounds.

This section discusses surface activities that could affect the geomorphological characteristics of the disposal system and result in changes in infiltration and recharge conditions. The potential effects of water use and control on disposal system performance are discussed in Section SCR.3.5.1.

SCR.3.4.1.1 Historical, Current, and Near-Future Human-Initiated EPs

Surface activities that take place at present in the vicinity of the WIPP site include those associated with potash mining, oil and gas reservoir development, water extraction, and grazing. Additionally, a number of archeological investigations have taken place within the controlled area that were aimed at protecting and preserving cultural resources. Elsewhere in the Delaware Basin, sand, gravel, and caliche are produced through surface quarrying. Although these activities have involved **surface disruptions** within the Delaware Basin, they have not altered the characteristics of the disposal system significantly, and they have therefore been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system. There are no existing plans for changes in land use in the vicinity of the WIPP in the near future. Therefore, consistent with the criteria in 40 CFR § 194.32(c) and 40 CFR § 194.54(b), **land use changes** in the near future in the vicinity of the WIPP have been eliminated from performance assessment calculations on regulatory grounds.

SCR.3.4.1.2 Future Human-Initiated EPs

The criterion in 40 CFR § 194.25(a), concerned with predictions of the future states of society, requires that compliance assessments and performance assessments "shall assume that characteristics of the future remain what they are at the time the compliance application is prepared." Therefore, future **land use changes** in the vicinity of the WIPP have been eliminated from performance assessment calculations on regulatory grounds.

Criteria relating to future human activities in 40 CFR § 194.32(a) limit the scope of consideration of future human actions in performance assessments to mining and drilling. Therefore, the effects of future **surface disruptions** have been eliminated from performance assessment calculations on regulatory grounds.

SCR.3.5 Surface Hydrological EPs

SCR.3.5.1 Water Control and Use

The effects of historical, current, and near-future damming of streams and rivers, reservoirs, irrigation, and altered soil or surface water chemistry by human activities have been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system. Future damming of streams and rivers, reservoirs, irrigation, and altered soil or surface water chemistry by human activities have been eliminated from performance assessment calculations on regulatory grounds. The effects of lake usage have been eliminated from performance assessment calculations on regulatory grounds.

Irrigation and damming, as well as other forms of water control and use, could lead to localized changes in recharge, possibly leading to increased heads locally, thereby affecting flow directions and velocities in the Rustler and Dewey Lake. Surface activities, such as those associated with potash mining, could also affect soil and surface water chemistry. Note that the potential effects of geomorphological changes through land use are discussed in Section SCR.3.4.1.

SCR.3.5.1.1 Historical, Current, and Near-Future Human-Initiated EPs

In the WIPP area, two topographically low features, the Pecos River and Nash Draw, are sufficiently large to warrant consideration for damming. Dams and **reservoirs** already exist along the Pecos River. However, the Pecos River is far enough from the waste panels (12 miles [19 kilometers]) that the effects of **damming of streams and rivers** can be eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system. Nash Draw is not currently dammed, and based on current hydrological and climatic conditions, there is no reason to believe it will be dammed in the near future.

Irrigation uses water from rivers, lakes, impoundments, and wells to supplement the rainfall in an area to grow crops. Irrigation in arid environments needs to be efficient and involves the spreading of a relatively thin layer of water for uptake by plants, so little water would be expected to infiltrate beyond the root zone. However, some water added to the surface may infiltrate and reach the water table, affecting groundwater flow patterns. Irrigation currently takes place on a small scale within the Delaware Basin but not in the vicinity of the WIPP, and the extent of irrigation is not expected to change in the near future. Such irrigation has no significant effect on the characteristics of the disposal system. Thus, the effects of irrigation have been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system.

Potash mining effluent and runoff from oil fields have altered soil and surface water chemistry in the vicinity of the WIPP. However, the performance of the disposal will not be sensitive to soil and surface water chemistry. Therefore, **altered soil or surface water chemistry by human activities** has been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system. The effects of effluent from potash processing on groundwater flow are discussed in Section SCR.3.3.2.

Consistent with the criteria in 40 CFR § 194.32(c) and 40 CFR § 194.54(b), consideration of historical, current, and near-future human activities is limited to those activities that have occurred, or are expected to occur, in the vicinity of the disposal system. There are no large lakes in the vicinity of the WIPP and, therefore, human-initiated EPs related to **lake usage** have been eliminated from performance assessment calculations on regulatory grounds.

SCR.3.5.1.2 *Future Human-Initiated EPs*

The EPA has provided criteria relating to future human activities in 40 CFR § 194.32(a), that limit the scope of consideration of future human actions in performance assessments to mining and drilling. Therefore, the effects of future **damming of streams and rivers**, **reservoirs**, **irrigation**, **lake usage**, and **altered soil and surface water chemistry by human activities** have been eliminated from performance assessment calculations on regulatory grounds.

SCR.3.6 Climatic EPs

SCR.3.6.1 Anthropogenic Climate Change

The effects of anthropogenic climate change (acid rain, greenhouse gas effects, and damage to the ozone layer) have been eliminated from performance assessment calculations on regulatory grounds.

The effects of the current climate and natural climatic change are accounted for in performance assessment calculations, as discussed in Section SCR.6.4.9. However, human activities may also affect the future climate and thereby influence groundwater recharge in the

WIPP region. The effects of anthropogenic climate change may be on a local to regional scale (**acid rain**) or on a regional to global scale (**greenhouse gas effects** and **damage to the ozone layer**). Of these anthropogenic effects, only the greenhouse gas effect could influence groundwater recharge in the WIPP region. However, consistent with the future states assumptions in 40 CFR § 194.25(a), compliance assessments and performance assessments need not consider indirect anthropogenic effects on disposal system performance. Therefore, the effects of anthropogenic climate change have been eliminated from performance assessment calculations on regulatory grounds.

SCR.3.7 Marine EPs

SCR.3.7.1 Marine Activities

Historical, current, near-future, and future coastal water use, seawater use, and estuarine water use have been eliminated from performance assessment calculations on regulatory grounds.

This section discusses the potential for human-initiated EPs related to marine activities to affect infiltration and recharge conditions in the vicinity of the WIPP.

SCR.3.7.1.1 Historical, Current, and Near-Future Human-Initiated EPs

The WIPP site is more than 480 miles (800 kilometers) from the nearest seas, and hydrological conditions in the vicinity of the WIPP have not been affected by marine activities. Furthermore, consistent with the criteria in 40 CFR § 194.32(c) and 40 CFR § 194.54(b), consideration of historical, current, and near-future human activities is limited to those activities that have occurred or are expected to occur in the vicinity of the disposal system. Therefore, human-initiated EPs related to marine activities (such as **coastal water use**, **seawater use**, and **estuarine water use**) have been eliminated from performance assessment calculations on regulatory grounds.

SCR.3.7.1.2 Future Human-Initiated EPs

The EPA has provided criteria relating to future human activities in 40 CFR § 194.32(a) that limit the scope of consideration of future human actions in performance assessments to mining and drilling. Therefore, the effects of future marine activities (such as **coastal water use**, **seawater use**, and **estuarine water use**) have been eliminated from performance assessment calculations on regulatory grounds.

SCR.3.8 Ecological EPs

This section discusses the potential effects of agricultural activities and social and technological developments on the hydrogeology and geochemistry of the disposal system.

Ecological FEPs relating to plant, animal, soil, and human uptake of radionuclides are discussed in Section SCR.2.8.

SCR.3.8.1 Agricultural Activities

The effects of historical, current, and near-future ranching and arable farming have been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system. The effects of changes in future ranching and arable farming practices have been eliminated from performance assessment calculations on regulatory grounds. Fish farming has been eliminated from performance assessment calculations on regulatory grounds.

Agricultural activities could affect infiltration and recharge conditions in the vicinity of the WIPP. Also, application of acids, oxidants, and nitrates during agricultural practice could alter groundwater geochemistry.

SCR.3.8.1.1 Historical, Current, and Near-Future Human-Initiated EPs

Grazing leases exist for all land sections immediately surrounding the WIPP and grazing occurs within the controlled area (see Section 2.3.2.2). Although grazing and related crop production have had some control on the vegetation at the WIPP site, these activities are unlikely to have affected subsurface hydrological or geochemical conditions. The climate, soil quality, and lack of suitable water sources all mitigate against agricultural development of the region in the near future. Therefore, the effects of historical, current, and near-future **ranching** and **arable farming** have been eliminated from performance assessment calculations on the basis of low consequence to the performance of the disposal system. Consistent with the criteria in 40 CFR § 194.32(c) and 40 CFR § 194.54(b), agricultural activities, such as **fish farming**, that have not taken place and are not expected to take place in the near future in the vicinity of the WIPP have been eliminated from performance assessment calculations on regulatory grounds.

SCR.3.8.1.2 Future Human-Initiated EPs

The EPA has provided criteria relating to future human activities in 40 CFR § 194.32(a), that limit the scope of consideration of future human activities in performance assessments to mining and drilling. Also, the criterion in 40 CFR § 194.25(a), concerned with predictions of the future states of society, requires that compliance assessments and performance assessments "shall assume that characteristics of the future remain what they are at the time the compliance application is prepared." Therefore, the effects of changes in future agricultural practices (such as **ranching, arable farming**, and **fish farming**) have been eliminated from performance assessment calculations on regulatory grounds.

SCR.3.8.2 Social and Technological Developments

Demographic change and urban development in the near future and in the future have been eliminated from performance assessment calculations on regulatory grounds. Loss of records in the future is accounted for in performance assessment calculations.

Social and technological changes in the future could result in the development of new communities and new activities in the vicinity of the WIPP that could have an impact on the performance of the disposal system.

Demography in the WIPP vicinity is discussed in Section 2.3.2.1. The community nearest to the WIPP site is the town of Loving, 18 miles (29 kilometers) west-southwest of the site center. There are no existing plans for urban developments in the vicinity of the WIPP in the near future. Furthermore, the criterion in 40 CFR § 194.25(a), concerned with predictions of the future states of society, requires that compliance assessments and performance assessments "shall assume that characteristics of the future remain what they are at the time the compliance application is prepared." Therefore, **demographic change and urban development** in the vicinity of the WIPP and technological developments have been eliminated from performance assessment calculations on regulatory grounds.

Human activities will be prevented from occurring within the controlled area in the near future. However, performance assessments must consider the potential effects of human activities that might take place within the controlled area at a time when institutional controls cannot be assumed to eliminate completely the possibility of human intrusion. Consistent with 40 CFR § 194.41(b), the DOE assumes no credit for active institutional controls for more than 100 years after disposal. Also, consistent with 40 CFR § 194.43(c), the DOE assumes that passive institutional controls do not eliminate the likelihood of future human intrusion entirely. Thus, the ineffectiveness of institutional controls in the future, represented in the FEP list in Table SCR-3 as **loss of records**, is accounted for in performance assessment calculations.

SCR.4 Modeling Scenario Forming FEPs

The preceding sections of Appendix SCR present the results of applying the methodology for screening FEPs, presented in Section 6.2 of the main text of this application. This section lists the FEPs that remain after screening and identifies

- how each FEP is represented in the mathematical models used in the performance assessment calculations,
- which performance assessment code(s) and/or parameter(s) are used in the treatment of each FEP,
- the section(s) of the application that describe the treatment of the FEP in detail.

The FEPs that remain after screening are accounted for in performance assessment calculations either through explicit representation in the equations that form the mathematical models or implicitly through the specification of parameter values input to the performance assessment codes.[6] Tables SCR-5 and SCR-6 list the FEPs accounted for in calculations of disposal system performance under undisturbed and disturbed conditions respectively. In these tables, FEPs treated through explicit representation in the equations are incorporated as M, and those FEPs treated through the specification of parameters values are incorporated as P. FEPs incorporated as M generally require specification of parameter values as well. In some cases, a submodel is used to generate parameter values that are necessary for the solution of the basic governing equations of a computer code. FEPs incorporated by such submodels are generally denoted P. For example, the creep closure model provides porosity data to BRAGFLO and accounts for several FEPs incorporated as P.

Tables SCR-5 and SCR-6 provide a link between the scenario-forming FEPs that are used to build the scenarios described in Section 6.3 and the conceptual and mathematical models described in Section 6.4. Codes and models mentioned are discussed in Section 6.4 and in appendices referenced from there.

[6] Performance assessment codes are those employed directly in the performance assessment calculations: BRAGFLO, NUTS, PANEL, SECOFL2D, SECOTP2D, CUTTINGS_S, and CCDFGF.

Table SCR-5. The Treatment of FEPs in Undisturbed Performance Scenarios

FEP Categorization	FEP Incorporation	FEP Treatment	Chapter Section
NATURAL FEPs			
Geological FEPs			
Stratigraphy			
Stratigraphy	P	Accounted for in the BRAGFLO model geometry	2.1.3 6.4.2
Structural FEPs			
Seismic activity			
Seismic activity	P	Accounted for in the DRZ permeability used by BRAGFLO	6.4.5.3
Geochemical FEPs			
Dissolution			
Shallow dissolution	P	Accounted for in the Culebra transmissivity fields	6.4.6.2
Subsurface hydrological FEPs			
Groundwater characteristics			
Saturated groundwater flow	M	Accounted for in BRAGFLO treatment of two-phase flow, and in SECOFL2D representation of flow in the Culebra	2.2.1 6.4.5 6.4.6
Unsaturated groundwater flow	M	Accounted for in BRAGFLO treatment of two-phase flow	2.2.1 6.4.6
Fracture flow	M	Accounted for in SECOTP2D treatment of flow in the Culebra	6.4.6.2
Effects of preferential pathways	P	Accounted for in the Culebra transmissivity fields	6.4.6.2
Subsurface geochemical FEPs			
Groundwater geochemistry			
Groundwater geochemistry	P	Accounted for in the actinide source term model, and in the actinide transport and retardation model used by SECOTP2D	2.2.1 6.4.6.2
Geomorphological FEPs			
Physiography			
Physiography	P	Accounted for in BRAGFLO model geometry	2.1.4 6.4.2
Surface hydrological FEPs			
Groundwater recharge and discharge			
Groundwater discharge	P	Accounted for in specification of boundary conditions to SECOFL2D	2.2.2 6.4.10.2
Groundwater recharge	P	Accounted for in specification of boundary conditions to SECOFL2D	2.2.2 6.4.10.2

Table SCR-5. The Treatment of FEPs in Undisturbed Performance Scenarios (Continued)

FEP Categorization	FEP Incorporation	FEP Treatment	Chapter Section
Infiltration	P	Accounted for in specification of boundary conditions to SECOFL2D	2.2.2 6.4.10.2
Changes in surface hydrology			
Changes in groundwater recharge and discharge	P	Accounted for by the climate change model	2.5.1 6.4.9
Climatic FEPs			
Climate			
Precipitation (for example, rainfall)	P	Accounted for by the climate change model	2.5.1 6.4.9
Temperature	P	Accounted for by the climate change model	2.5.1 6.4.9
Climate change			
Meteorological			
Climate change	P	Accounted for by the climate change model	2.5.1 6.4.9
WASTE- AND REPOSITORY-INDUCED FEPs			
Waste and repository characteristics			
Repository characteristics			
Disposal geometry	P	Accounted for in BRAGFLO model geometry	3.2 6.4.3
Waste characteristics			
Waste inventory	P	Accounted for in the actinide source term model	4.1 6.4.3.5 6.4.3.3
Container characteristics			
Container material inventory	P	Accounted for in CDFs for gas generation rates used by BRAGFLO	6.4.3.3
Seal characteristics			
Seal geometry	P	Accounted for in BRAGFLO model geometry	3.8 6.4.4
Seal physical properties	P	Accounted for in seal parameter values used by BRAGFLO	6.4.4 6.4.3
Backfill characteristics			
Backfill chemical composition	P	Accounted for in the actinide source term model	6.4.3.4

Table SCR-5. The Treatment of FEPs in Undisturbed Performance Scenarios (Continued)

FEP Categorization	FEP Incorporation	FEP Treatment	Chapter Section
Radiological FEPs			
Radioactive decay			
Radionuclide decay and ingrowth	M	Accounted for in NUTS, PANEL and SECOTP2D	6.4.12.4
Geological and mechanical FEPs			
Excavation-induced fracturing			
Disturbed rock zone	P	Accounted for in BRAGFLO parameter values and materials definition	6.4.5.3
Excavation-induced changes in stress	P	Accounted for in the creep closure model in BRAGFLO	6.4.3.1
Rock creep			
Salt creep	P	Accounted for in the creep closure model in BRAGFLO	6.4.3.1
Changes in the stress field	P	Accounted for in the creep closure model in BRAGFLO	6.4.3.1
Roof falls			
Roof falls	P	Accounted for in the permeability of the DRZ used by BRAGFLO	6.4.5.3
Subsidence			
Subsidence	P	Accounted for in CDF for permeability of DRZ used by BRAGFLO	6.4.5.3
Effects of fluid pressure changes			
Disruption due to gas effects	M	Accounted for in BRAGFLO fracture model for Salado interbeds	6.4.5.2
Pressurization	M	Accounted for in BRAGFLO fracture model for Salado interbeds	6.4.5.2
Effects of explosions			
Gas explosions	P	Accounted for in the permeability of the DRZ used by BRAGFLO	6.4.5.3
Mechanical effects on material properties			
Consolidation of waste	P	Accounted for in the creep closure model in BRAGFLO	6.4.3.1
Consolidation of seals	P	Accounted for in seal parameters used by BRAGFLO	6.4.4
Mechanical degradation of seals	P	Accounted for in seal parameters used by BRAGFLO	6.4.4
Underground boreholes	P	Accounted for in seal parameters used by BRAGFLO	6.4.5.3

1 **Table SCR-5. The Treatment of FEPs in Undisturbed Performance Scenarios**
2 **(Continued)**
3

	FEP Categorization	FEP Incorporation	FEP Treatment	Chapter Section
4	**FEP Categorization**	**FEP Incorpor-ation**	**FEP Treatment**	**Chapter Section**
5	Subsurface hydrological and fluid dynamical FEPs			
6	Repository-induced flow			
7	Brine inflow	M	Accounted for in BRAGFLO treatment of two-phase flow	6.4.3.2
8	Wicking	P	Accounted for in BRAGFLO gas generation model	6.4.3.2
9	Effects of gas generation			
10	Fluid flow due to gas production	M	Accounted for in BRAGFLO treatment of two-phase flow	6.4.3.2
11	Geochemical and chemical FEPs			
12	Gas generation			
13	Microbial gas generation			
14	Degradation of organic material	M	Accounted for in BRAGFLO gas generation model	6.4.3.3
15	Effects of temperature on microbial gas generation	P	Accounted for in CDFs for gas generation rates used by BRAGFLO	6.4.3.3
16	Effects of biofilms on microbial gas generation	P	Accounted for in CDFs for gas generation rates used by BRAGFLO	6.4.3.3
17	Corrosion			
18	Gases from metal corrosion	M	Accounted for in BRAGFLO gas generation model	6.4.3.3
19	Chemical effects of corrosion	P	Accounted for in CDFs for gas generation rates used by BRAGFLO	6.4.3.3
20	Chemical speciation			
21	Speciation	P	Accounted for in the actinide source term model, and in actinide transport and retardation model in SECOTP2D	6.4.3.4 6.4.3.5
22	Precipitation and dissolution			
23	Dissolution of waste	P	Accounted for in the actinide source term model	6.4.3.5
24	Sorption			
25	Actinide sorption	M	Accounted for in actinide retardation model in SECOTP2D	6.4.3.6
26	Kinetics of sorption	P	Accounted for in actinide retardation model in SECOTP2D	6.4.6.2.1
27	Changes in sorptive surfaces	P	Accounted for in actinide retardation model in SECOTP2D	6.4.6.2.1

Table SCR-5. The Treatment of FEPs in Undisturbed Performance Scenarios (Continued)

FEP Categorization	FEP Incorporation	FEP Treatment	Chapter Section
Reduction-oxidation chemistry			
Effect of metal corrosion	P	Accounted for in the actinide source term model	6.4.3.5
Reduction-oxidation kinetics	P	Accounted for in the actinide source term model	6.4.3.5
Organic complexation			
Humic and fulvic acids	P	Accounted for in estimates of the colloidal actinide source term	6.4.3.6 6.4.6.2.2
Chemical effects on material properties			
Chemical degradation of seals	P	Accounted for in seal parameters in BRAGFLO	6.4.4
Microbial growth on concrete	P	Accounted for in seal parameters in BRAGFLO	6.4.4
Contaminant transport mode FEPs			
Solute transport			
Solute transport	M	Accounted for by NUTS in the Salado and SECOTP2D in the Culebra	6.4.5.4 6.4.6.2.1
Colloid transport			
Colloid transport	M	Advection and diffusion of humic colloids in the Culebra is estimated with SECOTP2D.	6.4.6.2.2
Colloid formation and stability	P	Accounted for in the colloidal actinide source term model.	6.4.3.6
Colloid filtration	M	Accounted for in treatment of transport for microbial and mineral fragment colloidal particles.	6.4.6.2.2
Colloid sorption	M	Accounted for in estimates of humic colloid retardation used by SECOTP2D.	6.4.6.2.2
Microbial transport			
Microbial transport	M	Accounted for by treatment of microbes as colloids.	6.4.6.2.2
Contaminant transport processes			
Advection			
Advection	M	Accounted for by NUTS in the Salado and SECOTP2D in the Culebra	6.4.5.4 6.4.6.2
Diffusion			
Diffusion	M	Accounted for by SECOTP2D in the Culebra	6.4.6.2 6.4.5.4
Matrix diffusion	M	Accounted for by SECOTP2D in the Culebra	6.4.6.2

Table SCR-5. The Treatment of FEPs in Undisturbed Performance Scenarios (Continued)

FEP Categorization	FEP Incorporation	FEP Treatment	Chapter Section
HUMAN-INITIATED EPs			
Excavation activities			
Excavation activities			
Potash mining	P	Potash mining outside the controlled area is accounted for by modifying the Culebra transmissivity fields used by SECOFL2D	6.4.6.2.3 6.4.12.8 6.4.13.8
Subsurface hydrological and geochemical EPs			
Borehole fluid flow			
Drilling-induced flow			
Drilling-induced geochemical changes	P	Accounted for in SECOPT2D in the Culebra	6.4.6.2
Fluid injection			
Fluid injection-induced geochemical changes	P	Accounted for in SECOTP2D in the Culebra	6.4.6.2
Flow through abandoned boreholes			
Borehole-induced geochemical changes	P	Accounted for in SECOTP2D in the Culebra	6.4.6.2
Excavation-induced flow			
Changes in groundwater flow due to mining	P	Potash mining outside the controlled area is accounted for by modifying the Culebra transmissivity fields used by SECOFL2D	6.4.6.2.3 6.4.12.8 6.4.13.8

Legend:

M FEP treated through explicit representation in the equations.
P FEP treated through the specification of parameters values.

Table SCR-6. The Treatment of FEPs in Disturbed Performance Scenarios (Disturbed Performance Scenarios include the Undisturbed Performance FEPs tabulated in Table SCR-5)

FEP Categorization	FEP Incorporation	FEP Treatment	Chapter Section
NATURAL FEPs			
Geological FEPs			
Stratigraphy			
Brine reservoirs	M	Accounted for in BRAGFLO for E scenarios	6.4.8 6.4.12.6
WASTE- AND REPOSITORY-INDUCED FEPs			
Waste and repository characteristics			
Waste characteristics			
Heterogeneity of waste forms	P	Accounted for in the waste activity probabilities used by CCDFGF	6.4.12.4
Contaminant transport mode FEPs			
Particulate transport			
Suspensions of particles	M	Accounted for in CUTTINGS_S treatment of releases through boreholes	6.4.7.1
Cuttings	M	Accounted for in CUTTINGS_S treatment of releases through boreholes	6.4.7.1
Cavings	M	Accounted for in CUTTINGS_S treatment of releases through boreholes	6.4.7.1
Spallings	M	Accounted for in CUTTINGS_S treatment of releases through boreholes	6.4.7.1
HUMAN-INITIATED EPs			
Geological EPs			
Drilling			
Oil and gas exploration	P	Drilling of deep boreholes[a] is accounted for in estimates of drilling frequency used by CCDFGF	2.3.1.2 6.4.7 6.4.12.2
Potash exploration	P	Drilling of deep boreholes is accounted for in estimates of drilling frequency used by CCDFGF	2.3.1.1 6.4.7 6.4.12.2

[a] Deep drilling means those drilling events in the Delaware Basin that reach or exceed a depth of 2,150 feet below the surface relative to where such drilling occurred.

Table SCR-6. The Treatment of FEPs in Disturbed Performance Scenarios (Disturbed Performance Scenarios include the Undisturbed Performance FEPs tabulated in Table SCR-5) (Continued)

FEP Categorization	FEP Incorporation	FEP Treatment	Chapter Section
Oil and gas exploitation	P	Drilling of deep boreholes is accounted for in estimates of drilling frequency used by CCDFGF	2.3.1.2 6.4.7 6.4.12.2
Other resources	P	Drilling of deep boreholes is accounted for in estimates of drilling frequency used by CCDFGF	2.3.1.3 6.4.7 6.4.12.2
Enhanced oil and gas recovery	P	Drilling of deep boreholes is accounted for in estimates of drilling frequency used by CCDFGF	2.3.1.2 6.4.7 6.4.12.2
Excavation activities			
Potash mining	P	Potash mining inside the controlled area is accounted for by modifying the Culebra transmissivity fields used by SECOFL2D	6.4.6.2.3 6.4.12.8 6.4.13.8
Subsurface hydrological and geochemical EPs			
Borehole fluid flow			
Drilling-induced flow			
Drilling fluid flow	M	Accounted for in spallings and direct brine release models	6.4.7.1
Drilling fluid loss	P	Accounted for in the BRAGFLO treatment of brine flow	6.4.7.1
Blowouts	M	Accounted for in spallings and direct brine release models	6.4.7.1.1
Drilling-induced geochemical changes	P	Accounted for by SECOTP2D in the Culebra	6.4.6.2
Flow through abandoned boreholes			
Natural borehole fluid flow	M	Accounted for in BRAGFLO treatment of long-term releases through boreholes	6.4.7.2 6.4.12.7 6.4.13
Waste-induced borehole flow	M	Accounted for in BRAGFLO treatment of long-term releases through boreholes	6.4.7 6.4.2.1
Borehole-induced geochemical changes	P	Accounted for by SECOTP2D in the Culebra	6.4.6.2

Table SCR-6. The Treatment of FEPs in Disturbed Performance Scenarios (Disturbed Performance Scenarios include the Undisturbed Performance FEPs tabulated in Table SCR-5) (Continued)

FEP Categorization	FEP Incorporation	FEP Treatment	Chapter Section
Excavation-induced flow			
Changes in groundwater flow due to mining	P	Potash mining inside the controlled area is accounted for by modifying the Culebra transmissivity fields used by SECOFL2D	6.4.6.2.3 6.4.12.8 6.4.13.8
Ecological EPs			
Social and technological developments			
Loss of records	P	Accounted for in estimates of the probability of inadvertent human intrusion.	6.3 6.4.7 6.4.12.1 6.4.12.2

Legend:

M FEP treated through explicit representation in the equations.

P FEP treated through the specification of parameters values.

REFERENCES

Anderson, R.Y., Dean, W.E., Jr., Kirkland, D.W., and Snider, H.I. 1972. Permian Castile Varved Evaporite Sequence, West Texas and New Mexico. *Geological Society of America Bulletin,* Vol. 83, No. 1, pp. 59 – 85.

Anderson, R.Y. 1978. *Deep Dissolution of Salt, Northern Delaware Basin, New Mexico.* Report to Sandia National Laboratories, Albuquerque, NM. WPO 29527 – 29530.

Argüello, J.G., and Torres, T.M. 1988. *Thermal Effects of RH-TRU Waste Emplacement on WIPP Storage Room Thermal/Structural Response.* SAND88-2217. Sandia National Laboratories, Albuquerque, NM.

Bachman, G.O. 1974. *Geologic Processes and Cenozoic History Related to Salt Dissolution in Southeastern New Mexico.* Open-File Report 74-194. U.S. Geological Survey, Denver, CO.

Bachman, G.O. 1980. *Regional Geology and Cenozoic History of Pecos Region, Southeastern New Mexico.* Open-File Report 80-1099. U.S. Geological Survey, Denver, CO.

Bachman, G.O. 1981. *Geology of Nash Draw, Eddy County, New Mexico.* Open-File Report 81-31. U.S. Geological Survey, Denver, CO.

Bachman, G.O. 1984. *Regional Geology of Ochoan Evaporites, Northern Part of Delaware Basin.* Circular 184, pp. 1 – 27. New Mexico Bureau of Mines and Mineral Resources, Socorro, NM.

Bachman, G.O. 1987. *Karst in Evaporites in Southeastern New Mexico.* SAND86-7078. Sandia National Laboratories, Albuquerque, NM. WPO 24006.

Bachman, G.O., Johnson, R.B., and Swenson, F.A. 1973. *Stability of Salt in the Permian Salt Basin of Kansas, Oklahoma, Texas, and New Mexico.* Open-File Report 4339-4. U.S. Geological Survey, Denver, CO.

Barnhart, B.J., Campbell, E.W., Martinez, E., Caldwell, D.E., and Hallett, R. 1980. *Potential Microbial Impact on Transuranic Wastes Under Conditions Expected in the Waste Isolation Pilot Plant (WIPP), Annual Report, October 1, 1978-September 30, 1979.* LA-8297-PR. Los Alamos National Laboratory, Los Alamos NM.

Batchelor, G.K. 1973. *An Introduction to Fluid Dynamics.* First paperback edition. Cambridge University Press, London, UK.

Beauheim, R.L. 1986. *Hydraulic-Test Interpretations for Well DOE-2 at the Waste Isolation Pilot Plant (WIPP) Site*. SAND86-1364. Sandia National Laboratories, Albuquerque, NM. WPO 27565.

Bennett, D.G. 1996. *Formation and Transport of Radioactive Gases. Summary Memo of Record for GG-8 and RNT-26.* Memo of 16 May, 1996. SWCF-A 1.2.07.3: PA: QA: TSK: GG-8,RNT-26, Sandia National Laboratories, Albuquerque, NM 39406.

Bennett, D.G. Read, D., Atkins, M., Glasser, F.P. 1992. A thermodynamic Model for Blended Cements II: Cement Hydrate Phases; Thermodynamic Values and Modeling Studies. *Journal of Nuclear Materials*, Vol. 190, pp. 315 – 315.

Berner, R.A. 1981. Kinetics of Weathering and Diagenesis. In *Kinetics of Geochemical Processes.* A.C. Lasaga, and R.J. Kirkpatrick, eds. Reviews in Mineralogy, Mineralogical Society of America, Washington, D.C. Vol. 8, pp. 111 – 133.

Borns, D.J., and Shaffer, S.E. 1985. *Regional Well-Log Correlation in the New Mexico Portion of the Delaware Basin.* SAND83-1798. Sandia National Laboratories, Albuquerque, NM. WPO 24511.

Borns, D.J., Barrows, L.J., Powers, D.W., and Snyder, R.P. 1983. *Deformation of Evaporites Near the Waste Isolation Pilot Plant (WIPP) Site.* SAND82-1069. Sandia National Laboratories, Albuquerque, NM. WPO 27532.

Brausch, L.M., Kuhn, A.K., Register, J.K. 1982. *Natural Resources Study, Waste Isolation Pilot Plant (WIPP) Project, Southeastern New Mexico.* WTSD-TME-3156. U.S. Department of Energy, Waste Isolation Pilot Plant.

Bredehoeft, J.D., Riley, F.S., and Roeloffs, E.A. 1987. Earthquakes and Groundwater. *Earthquakes and Volcanoes,* Vol. 19, No. 4, pp. 138 – 146.

Bruno, J., and Sandino, A. 1987. *Radionuclide Co-precipitation.* SKB Technical Report, No. 87-23, 19 pp. Swedish Nuclear Fuel and Waste Management Co., Stockholm, Sweden.

Burton, P.L., Adams, J.W., and Engwall, C. 1993. "History of the Washington Ranch, Eddy County, New Mexico," *New Mexico Geological Society Guidebook, 44th Field Conference, Carlsbad Region, New Mexico and West Texas.* Eds. D.W. Love, J.W. Hawley, B.S. Kues, J.W. Adams, G.W. Austin, and J.M. Barker. SAND93-1318J. New Mexico Geological Society, Roswell, NM. 65-67.

Chapman, J.B. 1986. *Stable Isotopes in Southeastern New Mexico Groundwater: Implications for Dating Recharge in the WIPP Area.* EEG-35, DOE/AL/10752-35. Environmental Evaluation Group, Santa Fe, NM.

Chappell, J., and Shackleton, N.J. 1986. Oxygen Isotopes and Sea Level. *Nature,* Vol. 324, No. 6093, pp. 137 – 140.

Christensen, C.L., Gulick, C.W., and Lambert, S.J., 1983. *Sealing Concepts for the Waste Isolation Pilot Plant (WIPP) Site*. SAND81-2195. Sandia National Laboratories, Albuquerque, NM. WPO 24405.

Claiborne, H.C., and Gera, F. 1974. *Potential Containment Failure Mechanisms and Their Consequences at a Radioactive Waste Repository in Bedded Salt in New Mexico.* ORNL-TM-4639. Oak Ridge National Laboratory, Oak Ridge, TN.

Corbet, T. 1995. *Two-Dimensional Assumption for Culebra Calculations. Summary Memo of Record for NS-9.* Memo of 21 September, 1995. SWCF-A 1.1.6.3: PA:QA: MGT:FSD. Sandia National Laboratories, Albuquerque, NM.

Cranwell, R.M., Guzowski, R.V., Campbell, J.E., and Ortiz, N.R. 1990. *Risk Methodology for Geologic Disposal of Radioactive Waste: Scenario Selection Procedure.* NUREG/CR-1667, SAND80-1429. Sandia National Laboratories, Albuquerque, NM.

Davies, P.B. 1983. Assessing the Potential for Deep-Seated Salt Dissolution and Subsidence at the Waste Isolation Pilot Plant (WIPP). In *State of New Mexico Environmental Evaluation Group Conference, WIPP Site Suitability for Radioactive Waste Disposal, Carlsbad, NM, May 12-13, 1983.* (Copy on file at the Nuclear Waste Management Library, Sandia National Laboratories, Albuquerque, NM as WPO 29533.)

Davies, P.B. 1989. *Variable Density Ground-Water Flow and Paleohydrology in the Waste Isolation Pilot Plant (WIPP) Region, Southeastern New Mexico.* Open File Report 88-490. U.S. Geological Survey.

Davis, J.A. and Kent, D.B. 1990. Surface Complexation Modeling in Aqueous Geochemistry. *Mineral-Water Interface Geochemistry*, M.F. Hochella and A.F. White, eds. Reviews in Mineralogy, Mineralogical Society of America, Washington, DC, Vol. 23, pp. 177 – 260.

Dawson, P.R. and Tillerson, J.R. 1978. *Nuclear Waste Canister Thermally Induced Motion.* SAND-78-0566. Sandia National Laboratories, Albuquerque, NM. WPO 27328.

Dence, M.R., Grieve, R.A.F., and Robertson, P.B. 1977. Terrestrial Impact Structures: Principal Characteristics and Energy Considerations. In *Impact and Explosion Cratering,* D.J. Roddy, R.O. Pepin, and R.B. Merrill, eds. Pergamon Press, New York, NY, pp. 247 – 275.

Dietz, R.S. 1961. Astroblemes. *Scientific American,* Vol. 205, No. 2, pp. 50 – 58.

DOE (U.S. Department of Energy), 1980. *Final Environmental Impact Statement, Waste Isolation Pilot Plant.* DOE/EIS-0026. Vol. 1-2. Washington, DC. WPO 38835, 38838 – 38839.

Dowding, C.H., and Rozen, A. 1978. Damage to Rock Tunnels from Earthquake Shaking. *Journal of the Geotechnical Engineering Division, American Society of Civil Engineers,* Vol. 104, No. GT2, pp. 175 – 191.

Economy, K.E., 1996. *Drilling into a Salado Zone of Contamination Within the Controlled Area; Drilling into a Non-Salado Zone of Contamination Within the Controlled Area. Summary Memo of Record for S-9 and NS-6.* SWCF-A 1.1.6.3:PA:QA:TSK:NS-6,S-9. Sandia National Laboratories, Albuquerque, NM. WPO 39495.

EPA (U.S. Environmental Protection Agency). 1985. 40 CFR Part 191: Environmental Standards for the Management and Disposal of Spent Nuclear Fuel, High-Level and Transuranic Radioactive Wastes; Final Rule. *Federal Register,* Vol. 50, No. 182, pp. 38066 – 38089, September 19, 1985. Office of Radiation and Air, Washington, DC. WPO 39132.

EPA (U.S. Environmental Protection Agency). 1993. 40 CFR Part 191: Environmental Standards for the Management and Disposal of Spent Nuclear Fuel, High-Level and Transuranic Radioactive Wastes; Final Rule. Federal Register, Vol. 58, No. 242, p. 66398, December 20, 1993.

EPA (U.S. Environmental Protection Agency). 1996. *Criteria for the Certification and Re-Certification of the Waste Isolation Pilot Plant's Compliance with the 40 CFR Part 191 Disposal Regulations, Background Information Document for 40 CFR Part 194.* EPA 402-R-96-002, January 1996, U.S. Environmental Protection Agency, Office of Radiation and Indoor Air, Washington, DC.

Francis, A.J. 1985. *Low-Level Radioactive Wastes in Subsurface Soils, In Soil Reclamation Processes: Microbiological Analyses and Applications.* R.L. Tate, III and D.A. Klein, eds. Marcel DeKker, Inc., New York, pp. 279-331.

Francis, A.J., and Gillow, J.B. 1994. *Effects of Microbial Gas Processes on Generation Under Expected Waste Isolation Pilot Plant Repository Conditions, Progress Report through 1992.* SAND93-7036. Sandia National Laboratories, Albuquerque, NM. WPO 26555.

Grieve, R.A.F. 1987. Terrestrial Impact Structures. *Annual Review of Earth and Planetary Sciences,* Vol. 15, pp. 245 – 270.

Halliday, I. 1964. The Variation in the Frequency of Meteorite Impact with Geographic Latitude. *Meteoritics,* Vol. 2, No. 3, pp. 271 – 278.

M

Hartmann, W.K. 1965. Terrestrial and Lunar Flux of Large Meteorites in the Last Two Billion Years. *Icarus,* Vol. 4, No. 2, pp. 157 – 165.

Hartmann, W.K. 1979. "Long-Term Meteorite Hazards to Buried Nuclear Waste Report 2." In *Assessment of Effectiveness of Geologic Isolation Systems: A Summary of FY-1978 Consultant Input for Scenario Methodology Development,* B.L. Scott, G.L. Benson, R.A. Craig, and M.A. Harwell, eds. PNL-2851. Pacific Northwest Laboratory, Richland, WA. VI-1 through VI-15 (Chapter 6).

Hicks, T.W. 1996. *Thermal Convection and Effects of Thermal Gradients. Summary Memo of Record for GG-4 and S-10.* Memo of 29 May, 1996. SWCF-A 1.2.07.3: PA: QA: TSK: S10,GG4. Sandia National Laboratories, Albuquerque, NM. WPO 31290.

Holt, R.M., and Powers, D.W. 1988. *Facies Variability and Post-Depositional Alteration within the Rustler Formation in the Vicinity of the Waste Isolation Pilot Plant, Southeastern New Mexico.* DOE/WIPP 88-004. U.S. Department of Energy, Carlsbad, NM. (This document is included as Appendix FAC.)

Imbrie, J., and Imbrie, J.Z. 1980. Modeling the Climatic Response to Orbital Variations. *Science.* Vol. 207, no. 4434, pp. 943-953.

Johnson, K.S. 1987. Development of the Wink Sink in West Texas due to Salt Dissolution and Collapse. In *Karst hydrology. Proc. 2nd Conference, Orlando, 1987.* B.F. Beck, W.L. Wilson, eds. Oklahoma Geological Survey, Norman, USA. Balkema. pp. 127 – 136.

Kärnbränslesakerhet. 1978. *Handling of Spent Nuclear Fuel and Final Storage of Vitrified High Level Reprocessing Waste.* Kärnbränslesakerhet (now SKB), Stockholm, Sweden.

Kato, C., Sato, T., Smorawinska, M. and Horikoshi, K. 1994. "High Pressure Conditions Stimulate Expression of Chloramphenicol Acetyltransferase Regulated by the *lac* Promoter in *Escherichia coli," FEMS Microbiology Letters.* Vol. 122, nos. 1–2, 91 – 96.

King, P.B. 1948. *Geology of the Southern Guadalupe Mountains, Texas.* Professional Paper 215. U.S. Geological Survey, Washington, DC.

Lambert, S.J. 1983. *Dissolution of Evaporites in and around the Delaware Basin, Southeastern New Mexico and West Texas.* SAND82-0461. Sandia National Laboratories, Albuquerque, NM. WPO 27520.

Lambert, S.J., and Harvey, D.M. 1987. *Stable-Isotope Geochemistry of Groundwaters in the Delaware Basin of Southeastern New Mexico.* SAND87-0138. Sandia National Laboratories, Albuquerque, NM. WPO 24150.

Lappin, A.R., Hunter, R.L., Garber, D.P., Davies, P.B., Beauheim, R.L., Borns, D.J., Brush, L.H., Butcher, B.M., Cauffman, T., Chu, M.S.Y., Gomez, L.S., Guzowski, R.V., Iuzzolino, H.J., Kelley, V., Lambert, S.J., Marietta, M.G., Mercer, J.W., Nowak, E.J., Pickens, J., Rechard, R.P., Reeves, M., Robinson, K.L., and Siegel, M.D, eds. 1989. *Systems Analysis, Long-Term Radionuclide Transport, and Dose Assessments, Waste Isolation Pilot Plant (WIPP), Southeastern New Mexico, March 1989.* SAND89-0462. Sandia National Laboratories, Albuquerque, NM. WPO 24125.

Lasaga, A.C., Soler, J.M., Ganor, J., Burch, T.E., and Nagy, K.L. 1994. Chemical Weathering Rate Laws and Global Geochemical Cycles. *Geochimica et Cosmochimica Acta*, Vol. 58, No. 10, pp. 2361 – 2386.

Lenhardt, W.A. 1988. Damage Studies at a Deep Level African Gold Mine. In *Rockbursts & Seismicity in Mines, Proceeding of the Second International Symposium, Minneapolis, MN, June 8-10, 1988,* C. Fairhurst, ed., pp. 391 – 393. A.A. Balkema, Brookfield, VT.

Logan, S.E., and Berbano, M.C. 1978. *Development and Application of a Risk Assessment Method for Radioactive Waste Management.* EPA 520/6-78-005. U.S. Environmental Protection Agency, Washington, DC. Vols. 1 – 4.

Loken, M.C. 1994. SMC Thermal Calculations, RSI Calculation No. A141-GE-05, prepared for Parsons Brinckerhoff, San Francisco, CA. RE/SPEC, Inc., Rapid City, SD.

Loken, M.C. and Chen, R. 1994. Rock Mechanics of SMC, RSI Calculation No. A141-GE-07, prepared for Parsons Brinckerhoff, San Francisco, CA. RE/SPEC Inc., Rapid City, SD.

Lowenstein, T.K. 1987. *Post Burial Alteration of the Permian Rustler Formation Evaporites, WIPP Site, New Mexico: Textural, Stratigraphic and Chemical Evidence*. EEG-36, DOE/AL/10752-36. Environmental Evaluation Group, Santa Fe, NM.

Molecke, M.A. 1979. *Gas Generation from Transuranic Waste Degradation*. SAND79-0911C. Sandia National Laboratories, Albuquerque, NM. WPO 28093.

Muehlberger, W.R., Belcher, R.C., and Goetz, L.K. 1978. Quaternary Faulting on Trans-Pecos, Texas. *Geology,* Vol. 6, No. 6, pp. 337 – 340.

NMBMMR (New Mexico Bureau of Mines and Mineral Resources). 1995. *Final Report Evaluation of Mineral Resources at the Waste Isolation Pilot Plant (WIPP) Site.* NMBMMR, Campus Station, Socorro, NM, March 31, 1995.

Nicholson, A., Jr., and Clebsch, A., Jr. 1961. *Geology and Ground-Water Conditions in Southern Lea County, New Mexico.* Ground-Water Report 6. New Mexico Bureau of Mines and Mineral Resources, Socorro, NM.

Papenguth, H.W., and Behl, Y.K. 1996. Test Plan for Evaluation of Colloid-Facilitated Actinide Transport at the WIPP. TP 96-01, Sandia National Laboratories, Albuquerque, NM. WPO 31337.

Pedersen, K., and Karlsson, F. 1995. *Investigations of Subterranean Microorganisms: Their Importance for Performance Assessment of Radioactive Waste Disposal.* SKB Technical Report 95-10, Swedish Nuclear Fuel and Waste Management Co., Stockholm, Sweden.

Popielak, R.S., Beauheim, R.L, Black, S.R., Coons, W.E., Ellingson, C.T., and Olsen, R.L. 1983. *Brine Reservoirs in the Castile Formation, Waste Isolation Pilot Plant (WIPP) Project, Southeastern New Mexico.* TME-3153. U.S. Department of Energy, Carlsbad, NM.

Powers, D.W., Lambert, S.J., Shaffer, S.E., Hill, L.R., and Weart, W.D., eds. 1978. *Geological Characterization Report, Waste Isolation Pilot Plant (WIPP) Site, Southeastern New Mexico.* SAND78-1596, Vols. I and II. Sandia National Laboratories, Albuquerque, NM. (This document is included as Appendix GCR.) WPO 5448 (Volume 1); WPO 26829 – 26830 (Volume 2).

Rate, A.W., McLaren, R.G., and Swift, R.S. 1993. Response of Copper(II)-Humic Acid Dissociation Kinetics to Factors Influencing Complex Stability and Macromolecular Conformation. *Environmental Science Technology*, Vol. 27, pp. 1408-1414.

Rawson, D., Boardman, C., and Jaffe-Chazan, N. 1965. *Project Gnome, the Environment Created by a Nuclear Explosion in Salt.* PNE-107F. Lawrence Radiation Laboratory, University of California, Livermore, CA; Available from National Technical Information Service, Springfield, VA.

Rechard, R. P., Iuzzolino, H. , and Sandha, J. S., 1990. *Data Used in Preliminary Performance Assessment of the Waste Isolation Pilot Plant (1990).* SAND89-2408. Sandia National Laboratories, Albuquerque, NM.

Reed, D.T., Okajima, S., Brush, L.H., and Molecke, M.A. 1993. *Radiolytically-Induced Gas Production in Plutonium-Spiked WIPP Brine.* Scientific Basis for Nuclear Waste Management XVI, Materials Research Society Symposium Proceedings, Boston, MA, November 30 - December 4, 1992. C.G. Interrante and R.T. Pabalan, eds. SAND92-7283C. Materials Research Society, Pittsburgh, PA. Vol. 294, pp. 431 – 438.

Rechard, R.P., Stockman, C.T., Sanchez, L.C., Liscum-Powell, J., and Rath, J.S. 1996. Nuclear Criticality in Near Field and Far Field. Summary Memo of Record for RNT-1. SWCF-A:1.2.07.3:PA:QA:TSK:RNT-1. Sandia National Laboratories, Albuquerque, NM. WPO 40818.

Robinson, J.Q., and Powers, D.W. 1987. A Clastic Deposit Within the Lower Castile Formation, Western Delaware Basin, New Mexico. In *Geology of the Western Delaware*

Basin, West Texas and Southeastern New Mexico, D.W. Powers and W.C. James, eds. El Paso Geological Society Guidebook 18. El Paso Geological Society, El Paso, TX, pp. 69 – 79.

Rosholt, J.N., and McKinney, C.R. 1980. *Uranium Series Disequilibrium Investigations related to the WIPP Site, New Mexico. Part II, Uranium Trend Dating of Surficial Deposits and Gypsum Spring Deposits near WIPP Site, New Mexico,* Open-File Report 80-879, U.S. Geological Survey, Denver, CO.

Sanchez, L. C., and Trellue, H. R. 1996. Estimation of Maximum RH-TRU Thermal Heat Load for WIPP. Memo to T. Hicks (Galson Sciences Ltd.), January 17, 1996. Sandia National Laboratories, Albuquerque, NM. WPO 31165.

Sandia WIPP Project. 1992. *Preliminary Performance Assessment for the Waste Isolation Pilot Plant, December 1992. Volume 3: Model Parameters.* SAND92-0700/3, Sandia National Laboratories, Albuquerque, NM. WPO 28529.

Schiel, K.A. 1994. A New Look at the Age, Depositional Environment and Paleogeographic Setting of the Dewey Lake Formation (Late Permian). *West Texas Geological Society Bulletin,* Vol. 33, No. 9, pp. 5 – 13. WPO 20465.

Serne, R.J. 1992. "Current Adsorption Models and Open Issues Pertaining to Performance Assessment." In *Proceedings of the DOE/Yucca Mountain Site Characterization Project Radionuclide Adsorption Workshop at Los Alamos National Laboratory, September 11-12, 1990.* Comp. J.A. Canepa. LA-12325-C. Los Alamos National Laboratory, Los Alamos, NM. 43 – 74.

Siegel, M.D., Lambert, S.J., and Robinson, K.L. eds. 1991. *Hydrogeochemical Studies of the Rustler Formation and Related Rocks in the Waste Isolation Pilot Plant Area, Southeastern New Mexico.* SAND88-0196. Sandia National Laboratories, Albuquerque, NM.

Silva, M.K. 1994. *Implications of the Presence of Petroleum Resources on the Integrity of the WIPP.* EEG-55. Environmental Evaluation Group, Albuquerque, NM.

Snelling, A.A. 1992. *Alligator Rivers Analogue Project Final Report, Volume 2, Geologic Setting.* UK DOE Report DOE/HMIP/RR/92/072, SKI Report SKI TR 92:20-2, ISBN 0-642-59928-9. Her Majesty's Inspectorate of Pollution of the Department of the Environment, London; Swedish Nuclear Fuel and Waste Management Co., Stockholm, Sweden.

Snyder, R.P., Gard, Jr., L.M., and Mercer, J.W. 1982. *Evaluation of Breccia Pipes in Southeastern New Mexico and Their Relation to the Waste Isolation Pilot Plant (WIPP) Site.* Open-File Report 82-968. U.S. Geological Survey, Denver, CO.

Stoelzel, D.M., and O'Brien, D.G. 1996. The Effects of Salt Water Disposal and Waterflooding on WIPP. Summary Memo of Record for NS-7a. Sandia National Laboratories, Albuquerque, NM. WPO 40837.

Stroes-Gascoyne, S., and West, J.M. 1994. *Microbial Issues Pertaining to the Canadian Concept for the Disposal of Nuclear Fuel Waste.* AECL Report No. AECL-10808, COG-93-54. Atomic Energy of Canada Ltd., Whiteshell Labs, Pinawa, Manitoba, Canada. pp. 39.

Swift, P.N. 1992. *Long-Term Climate Variability at the Waste Isolation Pilot Plant, Southeastern New Mexico, USA*. SAND91-7055. Sandia National Laboratories, Albuquerque, NM. WPO 27093.

Telander, M.R., and Westerman, R.E. 1993. *Hydrogen Generation by Metal Corrosion in Simulated Waste Isolation Pilot Plant Environments: Progress Report for the Period November 1989 through 1992.* SAND92-7347. Sandia National Laboratories, Albuquerque, NM. WPO 23456.

Telford, W.M., Geldart, L.P., Sheriff, R.E. and Keys, D.A. 1976. *Applied Geophysics.* Cambridge University Press, Cambridge.

Thorne, B.J., and Rudeen, D.K. 1981. *Regional Effects of TRU Repository Heat.* SAND80-7161. Sandia National Laboratories, Albuquerque, NM. WPO 10281.

Thorne, M.C. 1992. *Dry Run 3 - A Trial Assessment of Underground Disposal of Radioactive Wastes Based on Probabilistic Risk Analysis - Volume 8: Uncertainty and Bias Audit.* DOE/HMIP/RR/92.040. Her Majesty's Inspectorate of Pollution (HMIP) of the Department of the Environment, London.

Tipping, E. 1993. Modeling the Competition between Alkaline Earth Cations and Trace Metal Species for Binding by Humic Substances. *Environmental Science & Technology* Vol. 27, pp. 520 – 529.

Vaughn, P., Lord, M., Garner, J. and MacKinnon, R. 1995. *Radiolysis of Brine*. Errata to Summary Memo of Record GG-1, SWCF-A:1.1.6.3:PA:QA:TSK:GG1,S7, December 21, 1995. Sandia National Laboratories, Albuquerque, NM. WPO 30786.

Waber, N. 1991. *Mineralogy, Petrology and Geochemistry of the Poços de Caldas Analogue Study Sites, Minas Gerais, Brazil, I. Osamu Utsumi Uranium Mine.* Nagra Report NTB-90-20. National Genossen Schaft für die Lagerung Radioaktiver Abfalle (NAORA), Baden, Switzerland.

Wakeley L. D., Harrington P. T., and Hansen F. D., 1995. *Variability in Properties of Salado Mass Concrete.* SAND94-1495. Sandia National Laboratories, Albuquerque, NM. WPO 22744.

Wallace, M. 1996a. Leakage from abandoned boreholes. Summary Memo of Record for NS-7b. SWCF-A 1.1.6.3:PA:QA:TSK:NS-7b. Sandia National Laboratories, Albuquerque, NM. WPO 40819.

Wallace, M. 1996b. *Pumping from the Culebra Outside the Controlled Area. Summary Memo of Record for NS-5.* SWCF-A 1.1.6.3:PA:QA:TSK:NS-5. Sandia National Laboratories, Albuquerque, NM. WPO 40831.

Wallace, M. 1996c. *Subsidence Associated with Mining Inside or Outside the Controlled Area. Summary Memo of Record for NS-11.* SWCF-A 1.1.6.3:PA:QA:TSK:NS-11. Sandia National Laboratories, Albuquerque, NM, Planning memo of record. WPO 40816.

Wallace, M., Beauheim, R., Stockman, C., Alena Martell, M., Brinster, K., Wilmot, R., and Corbert, T. 1995. Dewey Lake Data Collection and Compilation. Summary Memo of Record for NS-1. SWCF-A 1.1.6.3:PA:QA:TSK:NS-1. Sandia National Laboratories, Albuquerque, NM.

Wallner, M. 1981. Critical Examination of Conditions for Ductile Fracture in Rock Salt. In *Proceedings of the Workshop on Near-Field Phenomena in Geologic Repositories for Radioactive Waste, Seattle, WA, August 31-September 3, 1981*, pp. 243 – 253. Organisation for Economic Co-operation and Development, Paris, France.

Warrick, R., and Oerlemans, J. 1990. "Sea Level Rise." In *Climate Change: The IPCC Scientific Assessment,* J.T. Houghton, G.J. Jenkins, and J.J. Ephraums, eds., pp. 257 – 281. Intergovernmental Panel on Climate Change, Sweden, pp. 257 – 281.

Westinghouse Electric Corporation. 1994. *Backfill Engineering Analysis Report, Waste Isolation Pilot Plant.* Westinghouse Electric Corporation, Carlsbad, NM. WPO 37909.

Wilmot, R.D., and Galson, D.A. 1996. *Human-Initiated Brine Density Changes. Summary Memo of Record for NS17 and NS18.* SWCF-A 1.1.6.3:PA:QA:TSK; NS-17, NS-18. Sandia National Laboratories, Albuquerque, NM. WPO 39424.

WIPP Division, 1991. *Preliminary Comparison with 40 CFR Part 191, Subpart B for the Waste Isolation Pilot Plant, December 1991. Volume 1: Methodology and Results.* SAND91-0893/1, Sandia National Laboratories, WIPP Performance Assessment Division, Albuquerque, NM.

Wolery, T.J. 1992. *EQ3NR, A Computer Program for Geochemical Aqueous Speciation-Solubility Calculations: Theoretical Manual, Users guide, and Related Documentation (Version 7.0).* Lawrence Livermore National Report No. UCRL-MA-110662 PT III, pp. 1 – 246.

BIBLIOGRAPHY

Bennett, D.G., Wang, Y., and Hicks, T.W. 1996. An Evaluation of Heat Generation Processes for the WIPP. Memo of 20 August, 1996. SWCF-A (Org. 6352), WBS 1.1.09.1(RC).

Blackwell, D.D., Steele, J.L., and Carter, L.S. 1991. "Heat-Flow Patterns of the North American Continent; A Discussion of the Geothermal Map of North America." In *Neotectonics of North America,* D.B. Slemmons, E.R. Engdahl, M.D. Zoback, and D.D. Blackwell, eds., Geological Society of America, Boulder, CO. pp. 423 – 436.

Chapman, J.B., and Hokett, S.L. 1991. *Evaluation of Groundwater Monitoring at Offsite Nuclear Test Areas.* DOE/NV/10845-07. Prepared by the Water Resources Center of the Desert Research Institute for the Nevada Operations Office, U.S. Department of Energy, Las Vegas, NV.

Crawford, M.B. 1996. *Effects of Microbial Growth and Chemistry on Concrete Performance Summary Memo of Record for SP-5 and SP-8.* Memo of 22 May, 1996. SWCF-A 1.2.07.3: PA: QA: TSK: SP-5,SP-8. Sandia National Laboratories, Albuquerque, NM. WPO 31298.

DOE (U.S. Department of Energy). 1995. *Waste Isolation Pilot Plant Transuranic Waste Baseline Inventory Report.* CAO-94-1005, Revision 1, February 1995. WIPP Technical Assistance Contractor for U.S. Department of Energy, Carlsbad, NM.

Earth Technology Corp. 1988. *Final Report for Time Domain Electromagnetic (TDEM) Surveys at the WIPP Site.* SAND87-7144, Sandia National Laboratories, Albuquerque, NM.

EPA (U.S. Environmental Protection Agency). 1985. *Background Information Document, Final Rule for High-Level and Transuranic Radioactive Wastes.* EPA 520/1-85-023. U.S. Environmental Protection Agency, Office of Radioactive Programs, Washington, D.C.

Knowles, M.K., and Howard, C.L. 1996. "Field and Laboratory Testing of Seal Materials Proposed for the Waste Isolation Pilot Plant." *Waste Management '96 Symposium, Tucson, AZ, February 25-29, 1996.* SAND95-2082C. WPO 30945.

Molecke, M.A., Argüello, J.G., and Beraún, R. 1993. *Waste Isolation Pilot Plant Simulated RH TRU Waste Experiments: Data and Interpretation Report.* SAND88-1314. Sandia National Laboratories, Albuquerque, NM. WPO 29406.

Peake, T. 1996. *WIPP -- Examination of Mining and Hydraulic Conductivity.* Memo to Public Rulemaking Docket A-92-56. January 31, 1996.

Read, D., ed. 1994. *Chemval-2 Project. Report on Stage 1: Status of Six Technical Areas.* Nuclear Science and Technology Report No. EUR 15151 EN, Commission of the European Communities, Luxembourg, p. 236.

Reiter, M., Barroll, M.W., and Minier, J. 1991. "An Overview of Heat Flow in Southwestern United States and Northern Chihuahua, Mexico." In *Neotectonics of North America,* D.B. Slemmons, E.R. Engdahl, M.D. Zoback, and D.D. Blackwell, eds., pp. 457 -- 466. Geological Society of America, Boulder, CO.

Richardson, R.M., and Reding, L.M. 1991. North American Plate Dynamics. *Journal of Geophysical Research,* Vol. 96, No. B7, 11, pp. 12,201 – 12,223.

Sanchez, L.C. 1996. *Identification of Important Radionuclides Used in Wipp Performance Assessment.* Memo to John F. Suermann, March 6, 1996. Sandia National Laboratories, Albuquerque, NM. WPO 37431.

Sanford, A.R., Jakasha, L.H., and Cash, D.J. 1991. Seismicity of the Rio Grand Rift in New Mexico. In *Neotectonics of North America,* D.B. Slemmons, E.R. Engdahl, M.D. Zoback, and D.D. Blackwell, eds., Geological Society of America, Boulder, CO. pp. 229 – 244.

Slezak, S., and Lappin, A. 1990. Potential for and Possible Impacts of Generation of Flammable and/or Detonable Gas Mixtures during the WIPP Transportation, Test, and Operational Phases. In Memorandum to D. Mercer and C. Fredrickson, January 5, 1990. Sandia National Laboratories, Albuquerque, NM. WPO 21224.

Thompson, G.A., and Zoback, M.L. 1979. Regional Geophysics of the Colorado Plateau. *Tectonophysics,* Vol. 61, Nos. 1 – 3, pp. 149 – 181.

Van Sambeek, L.L. 1987. *Thermal and Thermomechanical Analyses of WIPP Shaft Seals.* SAND87-7039. Sandia National Laboratories, Albuquerque, NM. WPO 24144.

Wang, Y. 1996. *Evaluation of the Thermal Effect of MgO Hydration for the Long-Term WIPP Performance Assessment.* Memo of May 9, 1996. Sandia National Laboratories, Albuquerque, NM. SWCF-A (Org. 6352), WBS 1.1.09.1.1(RC). WPO 37743.

Wang, Y. and Brush, L.H. 1996. *Estimates of Gas-Generation Parameters for the Long-Term WIPP Performance Assessment.* Memo to Martin S. Tierney, January 26, 1996. Sandia National Laboratories, Albuquerque, NM. WPO 31943.

Witherspoon, P. A., Wang, J. S. Y., Iwai, K., and Gale, J. E. 1980. Validity of Cubic Law for Fluid Flow in a Deformable Rock Fracture. *Water Resources Research,* Vol. 16, no. 6, pp. 1016-1024. WPO 38853.

Wood, B.J., Snow, R.E., Cosler, D.J., and Haji-Djafari, S. 1982. *Delaware Mountain Group (DMG) Hydrology - Salt Removal Potential, Waste Isolation Pilot Plant (WIPP) Project, Southeastern New Mexico*. TME 3166. U.S. Department of Energy, Albuquerque NM.

Zoback, M.L., and Zoback, M.D. 1980. State of Stress in the Conterminous United States. *Journal of Geophysical Research,* Vol. 85, No. B11, pp. 6113 – 6156.

Zoback, M.D., and Zoback, M.L. 1991. "Tectonic Stress Field of North America and Relative Plate Motions." In *Neotectonics of North America,* D.B. Slemmons, E.R. Engdahl, M.D. Zoback, and D.D. Blackwell, eds. Geological Society of America, Boulder, CO. pp. 339 – 366.

Zoback, M.L., Zoback, M.D., Adams, J., Bell, S., Suter, M., Suarez, G., Estabrook, C., and Magee, M. 1991. *Stress Map of North America.* Continent Scale Map CSM-5, Scale 1:5,000,000. Geological Society of America, Boulder, CO.

ATTACHMENT

Attachment 1 Development of a WIPP-Specific List of Features, Events, and Processes for the Compliance Certification Application

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