6.4.5.4 Actinide Transport in the Salado

The DOE considers ~~A~~***a***ctinide transport in the Salado ~~is considered by the DOE~~ to be a possible mechanism for release to the accessible environment. As in other areas of the disposal system, actinides in the Salado may be transported as dissolved species or as colloidal particles. Actinide transport is affected by a variety of processes that may occur along the flow path.

The DOE uses the NUTS code (see Appendix ***PA, Section PA-4.3*** ~~NUTS~~) to model the migration of radionuclides in the repository and surrounding formations. NUTS models radionuclide transport within all regions for which BRAGFLO computes brine and gas flow, and uses as input for each realization the corresponding BRAGFLO velocity field, pressures, porosities, saturations, and other model parameters including (for example) the geometrical grid, residual saturation, material map, and compressibility.

The PA uses NUTS ~~is used~~ in two ways ~~in the performance assessment~~. First, the code is used in a computationally fast tracer mode to identify those BRAGFLO realizations for which it is ~~not~~ ***un***necessary to do full transport calculations because contaminated brine never reaches the top of the salt or the accessible environment within the Salado. Such realizations ~~have no potential to~~ ***cannot*** contribute to the total integrated release of radionuclides from the disposal system. If the tracer calculation indicates a possibility of consequential release, a computationally slow calculation of the full transport of each radionuclide is performed ***(see Appendix PA, Section 6.7.2)***.

6.4.5.4.1 NUTS Tracer Calculations

All BRAGFLO realizations are evaluated using NUTS in a tracer mode to identify ~~those~~ realizations for which there is no possibility of radionuclides reaching the accessible environment. The tracer simulations consider an infinitely soluble, nondecaying, nondispersive, and nonsorbing species as a tracer element. The tracer is given a unit concentration in all waste disposal areas of 1 kilograms per cubic meter. If this tracer does not reach the selected boundaries (the top of the Salado and the land withdrawal boundary within the Salado) in a cumulative mass greater than or equal to 10^{-7} kilograms within 10,000 years, ~~then~~ it is assumed ~~that~~ there is no consequential release to these boundaries. If a cumulative mass greater than or equal to 10^{-7} kilograms does reach the selected boundaries within 10,000 years, a complete transport analysis is conducted. The value of 10^{-7} kilograms is selected because, regardless of the isotopic composition of the release, it corresponds to a normalized release less than 10^{-6} EPA units, ~~which is~~ the smallest release displayed in CCDF construction. The largest normalized release ***would be 9.98×10^{-7} EPA units, which corresponds*** ~~corresponding~~ to 10^{-7} kilograms of ~~would occur if the release were entirely~~ ^{241}Am***, if the release was entirely ^{241}Am*** ~~EPA units.~~

6.4.5.4.2 NUTS Transport Calculations

For ~~those~~ BRAGFLO realizations with greater than 10^{-7} kilograms reaching the boundaries in the tracer calculations, NUTS models the transport of five different species of radionuclides (^{241}Am, ^{239}Pu, ^{238}Pu, ^{234}U, and ^{230}Th). These radionuclides ~~represent a lumping of~~ ***represent*** a larger number of radionuclides, as discussed in ***Appendix TRU WASTE.*** For decay purposes, radionuclides ~~have been~~ ***were*** ~~lumped~~ ***grouped*** together based on similarities ***such as isotopes of***

the same element and those with similar half-lives, to simplify the calculations, as discussed in ***CCA Appendix WCA.3.2.3***. For transport purposes, solubilities are lumped to represent both dissolved and colloidal forms. These ~~lumpings~~ ***groupings*** simplify and expedite calculations.

NUTS models radionuclide transport by advection (see Appendix ***PA, Attachment MASS)*** ~~MASS, Section MASS.13.5~~). NUTS disregards sorptive and other retarding effects throughout the entire flow region. Physically, some degree of retardation must occur at ~~some~~ locations within the repository and the geologic media, and the disregard of retardation processes is therefore conservative. NUTS also disregards reaction-rate aspects of dissolution and colloid formation processes, and mobilization is assumed to occur instantaneously. Neither molecular nor mechanical dispersion is modeled in NUTS. These processes are assumed to be insignificant in comparison to advection, as discussed further in Appendix ***PA,*** ~~MASS~~ ***Attachment MASS,*** ~~(Section MASS.13.5)~~.

Colloidal actinides are subject to retardation by chemical interaction between colloids and solid surfaces and by clogging of small pore throats (that is, sieving). ~~It is expected that t~~***T***here will be some interaction of colloids with solid surfaces in the anhydrite interbeds. ***The*** ~~As well, because of the~~ low permeability of intact interbeds~~, it~~ is ***reason to*** expect~~ed that~~ pore apertures are small and some sieving will occur. However, colloidal particles, if not retarded, are transported slightly more rapidly than the average velocity of the bulk liquid flow. Because the effects on transport of slightly increased average pore velocity and retarding interactions with solid surfaces and sieving are offsetting, the DOE assumes residual effects of these opposing processes will be either small or beneficial and does not incorporate them in modeling of ~~the transport of~~ actinide~~s~~ ***transport*** in the Salado interbeds.

If brine that has been in the repository moves into interbeds, it is likely that mineral precipitation reactions will occur. Precipitated minerals may contain actinides as trace constituents. The beneficial effects of the possible mineral co-precipitation process are neglected in ~~performance assessment~~***PA***. Furthermore, colloidal-sized precipitates will behave like mineral-fragment colloids, which are destabilized by brines, quickly agglomerat~~e~~***ing*** and settl~~e~~***ing*** by gravity. The beneficial consequence of colloid precipitation is also disregarded in ~~performance assessment~~***PA***.

Additional processes that may impact transport in Salado interbeds are related to fractures, channeling, and viscous fingering. Interbeds contain natural fractures. Because of the low permeability of unfractured anhydrite, ~~it is expected that~~ most fluid flow occurring in interbeds will occur in fractures. Even though some properties of naturally fractured interbeds are characterized by in-situ tests (see Section 2.2.1.3), other uncertainty exists in the characteristics of the fracture network that may be created if gas pressure in the repository becomes high. The ~~performance assessment~~***PA*** modeling system accounts for the possible effects on porosity and permeability of fracturing ~~through the implementation of~~ ***through use of*** a fracturing model (see Section 6.4.5.2). ~~It is considered that t~~***T***he processes and effects associated with fracture dilation or fracture propagation that are not already captured by the ~~performance assessment~~***PA*** fracture model ***are*** ~~will be~~ negligible (see ***CCA*** Appendix MASS, Section MASS.13.3 and MASS Attachment 13.2). Of those processes not already incorporated, channeling is considered to have the greatest potential effect.

Channeling is the movement of fluid through the larger aperture portions of a fracture network (that is, areas of local high permeability). It could locally enhance actinide transport. However, it is assumed that the effects of channeled flow in existing or altered fractures will be negligible on the scale of the disposal system. The DOE believes this assumption ~~to be~~ ***is*** reasonable because processes that act to limit the effectiveness of channels or disperse actinides in them are likely to occur. First, if gas is present in the fracture network, it will be present as the nonwetting phase and will occupy the portions of the fracture network with relatively large apertures, where the highest permeabilities will exist locally. The presence of gas thus removes the most rapid transport pathways from the contaminated brine and decreases the impact of channeling. Second, brine penetrating the Salado from the repository is likely to be completely miscible with in-situ brine. Because of miscibility, diffusion or other local mixing processes will probably broaden fingers (reduce concentration gradients) until the propagating fingers are indistinguishable from the advancing front.

~~It is expected that g~~***G***as will ***likely*** penetrate the liquid-saturated interbeds as a fingered front rather than as a uniform front. Fingers form because of the difference in viscosity between the invading fluid (gas) and the resident fluid (liquid brine), and because of channeling effects. This process does not affect actinide transport, however, because actinides of interest are transported only in the liquid phase, ~~and the liquid phase~~ ***which*** will not displace gas in the relatively high-permeability regions because of capillary effects.

6.4.6 Units Above the Salado

The geology and hydrology of units above the Salado are discussed in Sections 2.1.3 and 2.2.1.4, respectively. In this section, the assumptions, simplifications, and models used in ~~performance assessment~~***PA*** ~~modeling~~ of these units are described. Because it is unlikely that these units will be impacted by ~~undisturbed performance~~***UP***, modeling ~~of~~ these units is performed mainly because regulations require ~~consideration of~~ ***considering*** the effects of inadvertent human intrusions. See Appendix ***PA, Attachment*** MASS***,*** ~~(~~Section ~~MASS.~~14 for additional discussion on the units above the Salado.

The principal purpose of BRAGFLO calculations for units above the Salado is to determine the quantity of brine entering each unit from an intrusion borehole or the shaft. It is unrealistic to assume that all flow up an intrusion borehole enters the Culebra. Accordingly, BRAGFLO parameters are specified ~~such~~ ***so*** that brine flow from the intrusion borehole is possible not only into the Culebra but also into the Magenta, Dewey Lake, and overlying units (as well as to the ground surface), depending on whether liquid rises above the Culebra in the intrusion borehole. Some of the assumptions regarding the properties of ~~the~~ units above the Salado are made specifically ~~because they~~ ***to*** allow model simplification and are conservative with respect to actinide transport in the Culebra (that is, ~~tend to cause~~ overestimates ~~of~~ release***s***).

Consistent with accepted stratigraphic conventions for the area, discussed in Section 2.1.3, the units above the Salado are subdivided into seven layers in ~~performance assessment~~***PA***; these are, in order of ~~lower-to-higher~~ ***lowest to highest***, the ***Los Medaños*** ~~unnamed lower member~~, the Culebra, the Tamarisk, the Magenta, the Forty-niner, the Dewey Lake, and the units above the Dewey Lake. The conceptual model for each of these layers is described sequentially in the following sections.

A fundamental assumption in the ~~conceptual model~~ ~~used in performance assessment~~***PA conceptual model*** for modeling actinide transport to the accessible environment in units above the Salado is that lateral actinide transport through rock formations is possible within the next 10,000 years only in the Culebra. This assumption is appropriate for several reasons relating to the properties of ~~the~~ other rock units and the groundwater basin conceptual model, ~~which are~~ discussed in following sections.

Section 2.2.1.4 describes the hydrology of the units above the Salado in terms of the groundwater basin conceptual model. Insight into ~~the process occurring in the~~ groundwater basin ***processes*** ~~obtained by modeling and other lines of evidence~~ indicates that ***it is possible to*** significant***ly*** ~~simplification of~~ ***simplify*** the hydrologic models in the units above the Salado ~~is possible~~ to obtain reasonable estimates of actinide transport (see Corbet and Knupp 1996; Appendix ***PA, Attachment*** MASS, Section MASS***-***14~~.2~~). Therefore, the DOE calculates actinide transport in the units above the Salado with a two-dimensional conceptual and mathematical model. The models used for actinide transport in the units above the Salado are a simplified implementation of the groundwater basin conceptual model. The mathematical model is implemented in the computer codes ***MODFLOW-2000*** ~~SECOFL2D~~ and SECOTP2D ***(see Appendix PA, Section PA-4.8)***.

6.4.6.1 ***The Los Medaños*** ~~Unnamed Lower Member~~

The ***Los Medaños (formerly the*** unnamed lower member of the Rustler***,*** ~~(Region 18~~ ***Row 25*** in Figures 6-14 and 6-15) rests above the Salado. Its transmissivity ~~has been~~ ***was*** measured (see Section 2.2.1.4.1.1) and ~~was~~ found to be low, which is consistent with expectations based on its anhydrite, gypsum, halite, clay, and siltstone composition (see Section 2.1.3.5.1). In ~~performance assessment~~***PA***, this member is treated as impermeable, which prevents liquid flow and actinides from entering this unit. The DOE assumes that because of the low permeability of the ***Los Medaños assumption*** ~~unnamed lower member~~ any brine entering it ***from***~~adjacent to~~ an intrusion borehole would be contained well within the site boundary for more than 10,000 years. ~~Therefore, t~~***T***his treatment is conservative~~, regarding estimated releases into the Culebra,~~ because allowing flow from a borehole or shaft into the ~~unnamed lower member~~ ***Los Medaños*** would, if anything, decrease flow into the Culebra. This would ~~have a tendency to~~ reduce the release of actinides from the Culebra to the accessible environment. In ~~performance assessment~~***PA***, the thickness of ~~the unnamed lower member~~ ***Los Medaños*** is 36 m (118 ft), and its permeability is zero.

6.4.6.2 The Culebra

The Culebra is represented in BRAGFLO as ***Row 26*** ~~Region 17~~ in Figures ~~6-13 and 6-14~~***6-14 and 6-15***. The model geometries for Culebra flow calculations and transport calculations are discussed in this section. Boundary and initial conditions for this geometry are discussed in Section 6.4.10.2. Supplementing the discussion in this section are additional details about the Culebra modeling provided in Section 6.4.13 and ~~Appendices~~ ***Appendix PA, Section PA-4.9.*** ~~SECOFL2D, SECOTP2D, MASS (Section MASS.15), and TFIELD (Sections TFIELD.2.2 and TFIELD.4).~~

Conceptually, radionuclides might be introduced into the Culebra through brine flow up the sealed shafts. However, the chief source of actinides in the Culebra is modeled as long-term releases from a borehole that intersects the repository. If radionuclides are introduced into the Culebra, they may be transported from the point of introduction by groundwater flowing naturally through the Culebra.

The Culebra is conceptualized as a~~ horizontal,~~ confined aquifer. For fluid flow, it is conceptualized as a heterogeneous porous medium ~~which is~~ represented by variations in transmissivity. A heterogeneous velocity field is used for transport calculations, but all other rock properties ***(e.g., porosity, K_d)*** are conceptualized as constant (homogeneous) across the model area. The Culebra is conceptualized as having two types of porosity; a portion ~~of the porosity is~~ associated with high-permeability features where transport occurs by advection, and the rest ~~of the porosity is~~ associated with low-permeability features where flow does not occur and retardation occurs by physical processes (diffusion) and chemical processes (sorption). This type of conceptual model is commonly referred to as ***"***double-porosity.***"*** In this conceptual model, transport and retardation of colloidal particles ~~is~~ ***are*** also considered. ~~In t~~***T***his section~~, the principal topic will be~~ ***addresses*** fluid flow in the Culebra. The transport and retardation of dissolved actinides will be discussed principally in Section 6.4.6.2.1. The transport and retardation of colloidal particles will be discussed principally in Section 6.4.6.2.2.

In the Culebra conceptual model used in ~~performance assessment~~***PA***, the spatial distribution of transmissivity in the Culebra is important. Other potentially important processes acting on Culebra flow and transport are climate change (Section 6.4.9 and ***CCA*** Appendix MASS, Section MASS.17) and the effects of subsidence caused by potash mining in the McNutt (Section 6.4.6.2.3 and ***CCA*** Appendix MASS, Section MASS.15.4).

The ~~SECOFL2D~~ ***MODFLOW-2000*** code uses two-dimensional horizontal grids to simulate groundwater flow. A regional grid approximately 14 miles × 19 miles (22 kilometers × 30 kilometers) ***(Figure 6-17)*** with spatially varying transmissivity (~~Figure 6-17~~) ~~is used to~~ determine***s*** the flow fields in the WIPP region ~~resulting~~ from hydraulic head distributions ~~that are~~ controlled by distant topographic and hydrologic features (that is, boundary conditions). ***The grid is made up of 68,768 uniform 100-m × 100-m (328.08-ft) cells.*** Because this grid is used to define the boundary conditions for the flow and transport calculations, it is discussed in detail in Section 6.4.10.2, ~~together~~ ***along*** with the specification of ~~initial and~~ boundary conditions. ***Details about the development and calibration of the flow fields are given in Appendix PA, Attachment TFIELD.*** For transport in the region of interest~~ within the disposal system~~, a local grid 7***.5*** km × ***5.4***~~7~~ km (4***.5*** mi × ~~4~~ ***3.1*** mi) with finer discretization is used in ~~both SECOFL2D and~~ SECOTP2D (~~Figure 6-18~~ ***Figure 6-18***). ~~Boundary heads and fluxes for the local grid are obtained by interpolation from the regional flow field. The grid for the local domain contains 75 columns and 65 rows, resulting in 4,875 grid blocks.~~ ***The grid for the transport domain contains 150 columns and 108 rows of 50 m × 50-m (164 ft) cells, resulting in 16,200 grid blocks.***

~~Boundaries of t~~***T***he local ***SECOTP2D*** domain ***boundaries (Figure 6-18)*** were chosen to capture ***all*** ~~important~~ flow paths ***from the modeled release point above the center of the disposal panels*** ~~and facilitate the computation of integrated release~~ to the accessible environment. Because past analyses ~~have~~ indicated that transport in the Culebra ~~will~~ occur***s*** within a region that lies from southeast of the repository to west of the repository, the ***transport*** ~~local~~ domain extends slightly beyond the southern and western boundaries of the controlled area. Because it is not needed, a strip in the northern portion of the controlled area has been omitted from the ~~local~~ ***SECOTP2D*** domain to ease the computational burden.

Flow directions and transmissivities in the Culebra vary significantly from location to location ~~to a considerable distance from~~ ***within and past*** the site boundary. Consequently, the effects of flow in the region around the WIPP site are ~~considered~~ important in the conceptual model. The boundaries to the flow model are discussed in Section 6.4.10.2; the ***domain*** ~~grid~~ itself is shown in ~~Figure 6-18~~ ***Figure 6-17***.

The conceptual model for the Culebra assumes that fluid fluxes and directions in the future will be the same as ~~they are projected to be~~ at repository closure, unless future mining within the site occurs, in which case changes to fluid flow are calculated. A steady-state flow field is used to represent this assumption. Conditions assumed at site closure are the subsidence effects of mining in the near future outside the site boundary, climate change, and ***heads similar to those measured in late 2000*** ~~a reasonable estimate of the hydraulic conditions that existed prior to disturbances to the Culebra caused by site characterization activities~~ (see Appendix ***PA, Attachment*** MASS, Sections MASS-15.4 and MASS-14.2, and ~~Appendix~~ ***Attachment*** TFIELD~~, Section TFIELD.2.2~~).

The factors controlling fluid flow in the Culebra are ~~conceptualized to be~~ the hydraulic gradient, ***distribution of*** transmissivity ~~distribution~~, and porosity. The hydraulic gradient and transmissivities used in ~~performance assessment~~***PA*** are coupled because they are calibrated to observed conditions by a process described in Appendix ***PA, Attachment*** TFIELD~~, (Section TFIELD.3)~~. Flow fields are calculated with the code ~~SECOFL2D~~ ***MODFLOW-2000*** ~~using an assumption of~~ ***assuming*** homogeneous porosity in the Culebra. This single value is the total porosity for the Culebra, including both advective and diffusive porosity, as discussed below. ~~Use of~~ ***Using*** a single porosity for the flow calculation does not introduce inconsistency with transport calculations because (1) steady-state flow fields are used so flux through the system is not dependent on porosity, and (2) the velocity of liquid for transport is calculated based on a double-porosity model implemented in ~~the code~~ SECOTP2D. Thus, the important factors for flow calculations are the hydraulic gradient and transmissivity variation.

Because BRAGFLO models a vertical section of the disposal system, the spatial distribution of transmissivity cannot be represented in the BRAGFLO grid. The source term of actinides in the Culebra is calculated in part from BRAGFLO flow fields, so parameters for the Culebra are required in BRAGFLO. Specifically, a single value of Culebra permeability representative for the Culebra in the area immediately over the waste-emplacement panels is input to partition fluid flow among the stratigraphic units along the human-intrusion borehole.

BRAGFLO calculates gas flow and brine flow that may occur up a borehole (see Section 6.4.7). The ***MODFLOW-2000*** ~~SECO~~ code models flow of the liquid phase only. The possible effects of gas on Culebra flow are not modeled ~~in the SECO codes~~. This simplification is reasonable because after gas pressure is relieved by flow to the surface during drilling, little gas will remain in the repository. This gas will move up the borehole at low rates and tend to move directly to the top of the liquid-saturated section of the borehole, bypassing the Culebra. Any gas that does

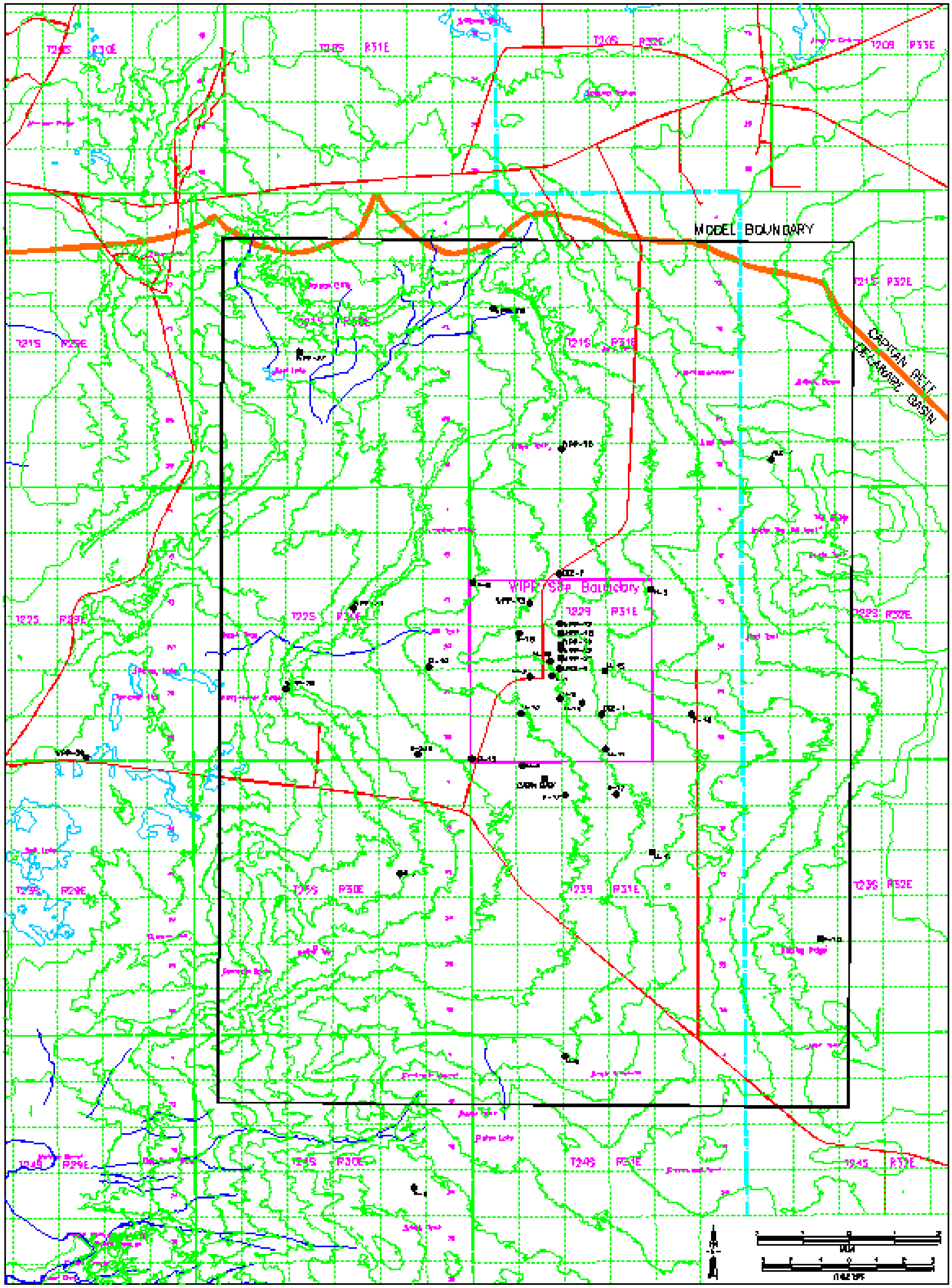


Figure 6-17. The MODFLOW-2000 Domain Used in the Groundwater Model of the Culebra

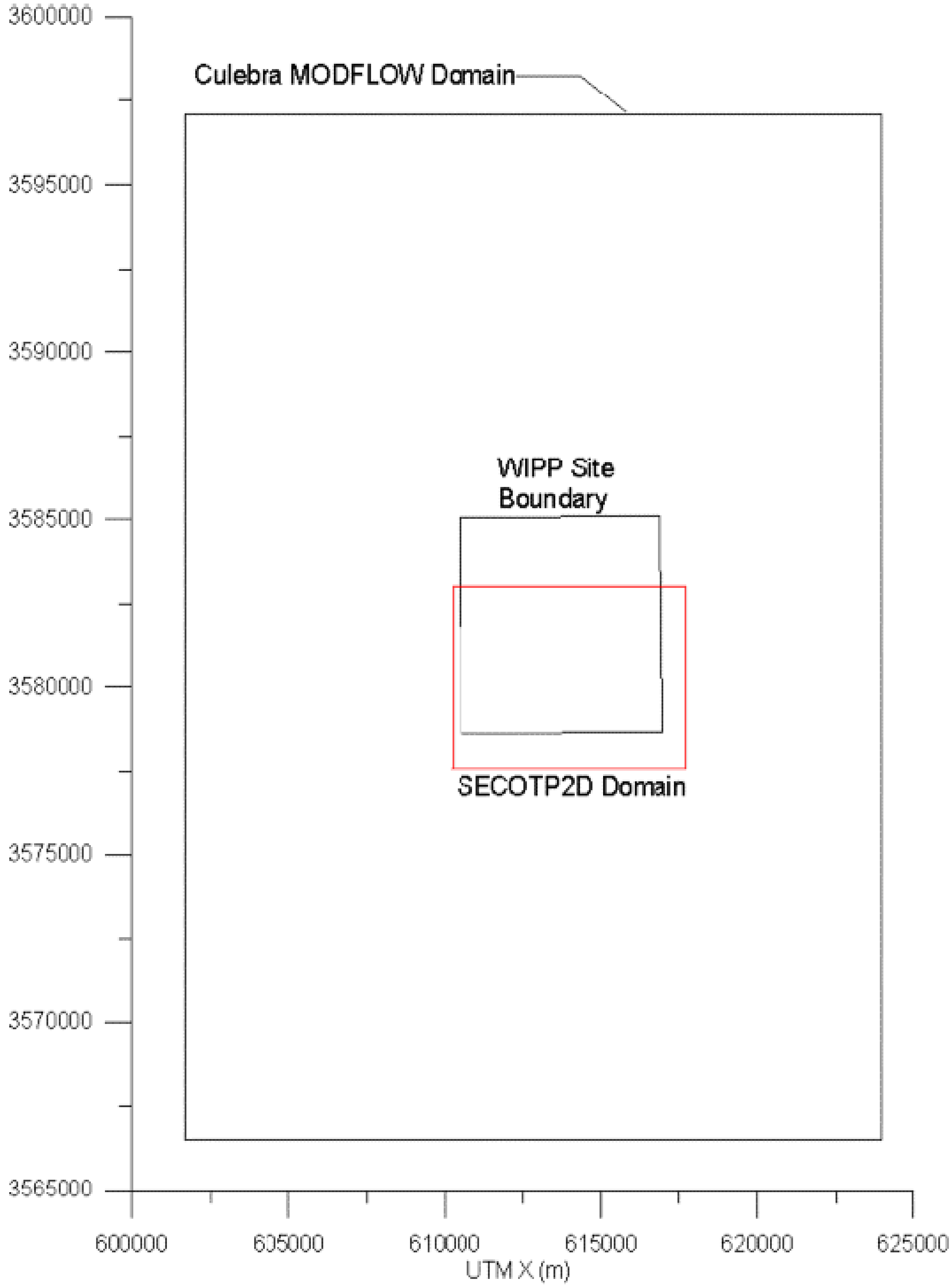


Figure 6-18. ***Extent of SECOTP2D Domain with Respect to the MODFLOW-2000 Culebra Domain and WIPP Site Boundary*** ~~**The Discretization Used in Modeling Groundwater Flow in the Culebra**~~

enter the Culebra will tend to displace brine from fractures and reduce the potential for actinide transport. Based on previous modeling (Lappin et al. 1989, Appendix E.1.5.1), the effect of the mass of brine being injected into the Culebra on the natural flow ~~in the Culebra~~ is negligible. Parameter values used in BRAGFLO to describe the Culebra are shown in ***Table 6-20***~~Table 6-18~~. Parameter values used in ~~SECOFL2D~~ ***MODFLOW-2000*** are shown in ***Table 6-21***~~Table 6-19~~. See Appendix ***PA, Attachment*** PAR***,*** ~~(~~Table ***2*** ~~PAR-30) and relevant Culebra parameter sheets,~~ for additional ***Culebra parameter*** information.

Three different thicknesses of the Culebra ~~have been~~ ***were*** assumed in ~~performance assessment~~***PA*** modeling. BRAGFLO uses a thickness of 7.7 m (25.3 ft), representative of the Culebra over the waste disposal panels. For calibrating transmissivity fields (see Appendix ***PA, Attachment*** TFIELD~~, Section 4.4.1~~) and calculating flow in the Culebra with ~~SECOFL2D~~ ***MODFLOW-2000***, a thickness of 7.75 m (25.4 ft) is assumed, consistent with an average thickness over the area modeled. For transport calculations using ~~the code~~ SECOTP2D, a thickness of 4 m (13 ft) is assumed, consistent with ~~observations of~~ the ***observed*** thickness of the Culebra active in transport, which ~~are~~ ***is*** discussed in Section 6.4.6.2.1. ~~Use of~~ ***Using*** different thicknesses does not introduce inconsistencies in the modeling, however, because the transmissivities used in these codes are consistent, and ~~it is this parameter that~~ ***transmissivity*** governs the total flux of fluid through the Culebra. Furthermore, the fluid flux used in the SECOTP2D model is ~~the same as that~~ calculated by ~~SECOFL2D~~ ***MODFLOW-2000***, ensuring consistency.

The spatial variation in transmissivity observed in the Culebra is incorporated by assigning different transmissivity values to every computational cell in the model. Because there is uncertainty in the estimated value of Culebra transmissivity ~~in areas~~ where measurements have

Table *6-20*~~6-18~~. Culebra Parameter Values for the BRAGFLO Model

Parameter (units)[~~a~~ 1]	Value
Permeability (square meters)	***7.73×10^{-14}*** ~~2.1×10^{-14}~~
Effective porosity (percent)	15.1
Rock compressibility (1/pascals)[~~b~~ 2]	10^{-10}
Threshold pressure, P_t (pascals)[~~c~~ 3]	1.5×10^4
Residual brine saturation, S_{br} (unitless)	0.084
Residual gas saturation, S_{gr} (unitless)	0.077
Pore distribution parameter, λ (unitless)	0.644
Maximum capillary pressure (pascals)	10^8
Thickness (meters)	7.70
Initial Pressure (pascals)	***9.14*** ~~8.22~~ $\times 10^5$

[~~a~~ 1] See ***Table 6-11*** ~~Table 6-9~~ for fluid properties in BRAGFLO.

[~~b~~ 2] Pore compressibility = rock compressibility/effective porosity.

[~~c~~ 3] Threshold pressure (***P***~~P_t~~) determined from relationship: $P_t = PCT\_A \cdot k^{PCT\_EXP}$, where PCT_A and PCT_EXP are constants and k is the permeability.

Table *6-21*~~6-19~~. ~~SECO~~ *MODFLOW-2000* Fluid Properties

Parameter (units)	Value
Liquid density (kilograms per cubic meter)	1,000
Liquid compressibility (1/pascals)	4.4×10^{-10}

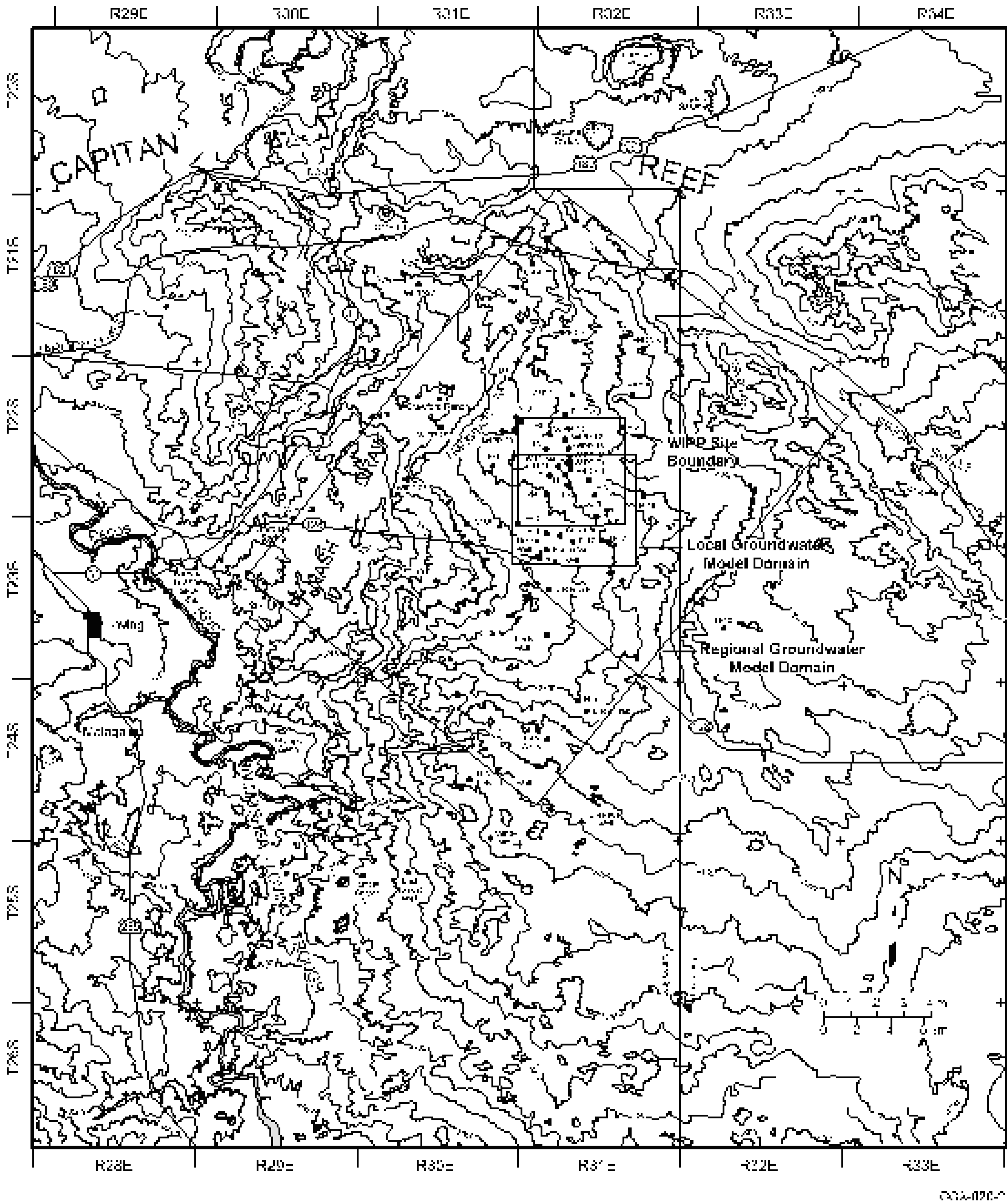
not been made, ***100 different*** ~~a large set of~~ transmissivity fields ~~is~~ ~~have been~~ ***were*** developed. Each transmissivity field ~~is a statistical representation of~~ ***statistically represents*** the natural variation in transmissivity that honors measured data according to certain criteria. ~~For a set of transmissivity fields generated with identical constraints, each field is equally likely to represent actual conditions.~~ Monte Carlo simulations using a large number of equally-likely transmissivity fields ~~is~~ ***are*** a statistically sound method of characterizing the uncertainty associated with transmissivity in the Culebra. For details of the generation and use of transmissivity fields ***and criteria***, refer to ***Appendix PA,*** ~~Appendix~~ ***Attachment*** TFIELD. ~~(Section TFIELD.4.1).~~

Regional flow directions and fluxes are calculated with the regional domain, as described earlier and shown in ~~Figure 6-17~~ ***Figure 6-18.*** ~~and 6-17.~~ ~~For~~***To*** increase~~d~~ resolution of transport processes ~~in the region where transport is important,~~ a finer grid is used. ***Within MODFLOW-2000, each 100-m × 100-m cell is divided into four 50-m × 50-m cells with exactly the same transmissivity as the 100-m × 100-m cell. Darcy velocities are calculated in the 50-m × 50-m cells and then mapped directly into the SECOTP2D grid (Figure 6-18), which also consists of 50-m × 50-m cells.*** Consistency between the flow calculated in the regional domain and flow in the local domain is important, and is assured by interpolation of the boundary conditions and transmissivity field properties of the regional domain onto the local domain. This process of calculating two flow fields with domains of different extent and ~~different~~ resolution ~~is implemented to~~ for practical reasons only. It is a method of incorporating regional effects in finely discretized local flow fields that has relatively low computational burden, compared to other possible methods. Additional discussion of this process is provided in Section 6.4.10.2.

In summary, flow in the Culebra is calculated with the code ***MODFLOW-2000***~~SECOFL2D~~, using a conceptual model of a ~~horizontal~~ confined aquifer, regional flow effects, uniform porous ~~media~~***medium***, steady state, and transmissivity variation. In addition, the effects of subsidence caused by potash mining in the McNutt are incorporated during the flow calculation, as discussed in Section 6.4.6.2.3.

6.4.6.2.1 Transport of Dissolved Actinides in the Culebra

Actinides may be introduced into the Culebra by brine flowing up a borehole or ~~by brine flowing~~ up the shaft. Three principal processes have been demonstrated to occur naturally that affect the transport and retardation of dissolved actinides. Dissolved actinides will be carried by advection in the natural flow of Culebra groundwater. Dissolved actinides will diffuse into the matrix. Dissolved actinides will sorb to varying extents onto the different minerals lining pore walls or fractures. It is possible that dissolved actinides may participate as trace constituents in reactions between water and rock and be bound ~~up~~ in newly formed minerals, but this phenomenon is not included in the conceptual model. These processes are complicated to characterize because of



~~Figure 6-17. The Regional and Local Domains Used in the Horizontal Groundwater Model of the Culebra~~

known stratigraphic variation in the Culebra and expected heterogeneity in solution chemistry along the possible flow paths from the injection point to the accessible environment.

The basic stratigraphy of the Culebra is continuous across the WIPP site (***CCA*** Appendix FAC, Section FAC.4.1.2), and ~~it~~ contains layers with significantly different properties (Holt and Powers 1984, 1986, 1990, and ***CCA*** Appendix FAC, Section FAC.5.2). Hydraulically, there

~~appear to be~~ ***are*** two distinct layers in the Culebra. Mercer and Orr (1979) report the result of a tracer and temperature survey that suggests there is ~~not~~ ***no*** significant flow in the upper 4.3 m (14 ft) of the Culebra. Culebra hydraulic testing at well H-14 indicates generally low permeabilities but a slightly higher permeability in the upper portion (Beauheim 1987). In descriptions from the air intake shaft, Holt and Powers (1990) noted that most of the fluid produced came ~~out of~~ ***from*** the lower portion of the Culebra. Hydraulic tests at the H-19 hydropad indicate that the permeability of the ~~upper portion of the~~ Culebra***'s upper portion*** is significantly lower than the permeability of the lower portion ***(Beauheim 2000)***. Consistent with hydraulic indicators, tracer tests conducted at H-19 confirmed that the ~~upper portion of the~~ Culebra***'s upper portion*** makes no significant contribution to the transport of dissolved species, although it may ~~act to~~ retard solute transport by diffusion into it ***(Meigs et al. 2000)***. The Culebra at the WIPP site is conceptualized as having very low permeability in the upper approximately 3 m (9.8 ft), and variable permeability in the lower portion, which can be lower than the upper portion in regions where the Culebra as a whole is relatively impermeable. Thus, the bulk of the data indicates that the majority of the flow and transport takes place in the lower portions of the Culebra. Accordingly, for ~~flow and~~ transport calculations, an effective thickness ~~of the Culebra~~ of 4 m (13.1 ft) is assumed ***(Meigs and McCord 1996)***.

There is considerable variability in the structure and size of porous features in the Culebra, including fractures (of a variety of dimensions and interconnectedness), vugs, ***and*** interparticle and intercrystalline porosity ***(Holt 1997)***. The principal flow occurs ~~within those~~ ***in*** features with the high permeability, and slower flow and diffusion are primary processes in ~~the~~ lower permeability features. Tracer test interpretations indicate that at some locations, flow occurs predominantly through fractures (advective porosity is low) and at other locations, slower transport indicates that flow ~~is occurring~~ ***occurs*** in other permeable features, such as vugs connected by microfractures, and possibly interparticle porosity (higher advective porosity). Tracer test interpretations also indicate that matrix diffusion is an important process in high-permeability regions of the Culebra. In other words, at least two scales of porosity are needed to ~~reasonably~~ represent the transport processes in the Culebra ~~reasonably~~ (that is, a double-porosity model). At some locations of low permeability, fractures may be absent or filled with gypsum. An alternative conceptual model for transport at these locations is uniform single porosity with a high porosity. To simplify calculations, the uniform single-porosity model was not implemented; the double-porosity model implemented results in faster transport.

In SECOTP2D, advective porosity represents the porous features in which flow occurs. Advective porosity values are low, which is representative of flow in fractures. Diffusive porosity represents those porous features in which no flow ~~is assumed to~~ occur***s*** and diffusion and sorption occur. Diffusive porosities are large relative to advective porosity, ~~representative of~~ ***representing*** the vugs, interparticle, and intercrystalline porosity of the bulk rock.

The processes that occur in the advective porosity portion of the Culebra are advection (flow), dispersion (spreading caused by heterogeneity), diffusion within the advective porosity, and diffusion into the diffusive porosity. Important factors in this conceptual model are the velocities of fluid in the advective porosity, free-water diffusion coefficients, and dispersion coefficients. The most important factor is the fluid velocity. Free-water tracer diffusion coefficients are specified for actinides. Dispersive spreading at the scale of disposal-system modeling is dominated by the effects of heterogeneities explicitly incorporated in the transmissivity fields input to ~~SECOFL2D~~ ***MODFLOW-2000***. This eliminates the need to account for larger-scale features by specifying a ~~dispersion coefficient for SECO~~ modeling ***dispersion coefficient*** larger than those observed at the hydropad-test scale.

Fluid velocity in SECOTP2D is coupled to the results of the fluid flow modeling conducted with ~~SECOFL2D~~ ***MODFLOW-2000*** ~~on the local domain~~ (see the preceding section). Fluid flow directions and volumetric fluxes in SECOTP2D are calculated in ~~SECOFL2D~~ ***MODFLOW-2000***. The flow velocities in the transport calculation are determined using the fluxes from the fluid flow calculation, the Culebra thickness specified for the transport calculation, and the advective porosity specified for the transport calculation. Because a different transmissivity field is used and the values of several important parameters are sampled, each realization uses a different velocity field.

Retardation is conceptualized ~~to be~~ ***as*** a function of physical effects of diffusion into diffusive porosity and sorption. Diffusion is parameterized by the diffusive porosity (which ~~can~~ ***is*** essentially ~~be thought of as~~ a reservoir for diffusion), tortuosity, matrix block length, and free-water diffusion coefficient. Tortuosity represents the tortuous structure of the porosity within the matrix; it ~~acts to~~ slow***s*** the diffusion process. The matrix block length is a conceptual construct representing the ratio of the surface area between advective and diffusive porosity to the volume of diffusive porosity features; physical retardation increases as the matrix block length decreases. Physical retardation also increases if tortuosity or the free-water diffusion coefficient of diffusive porosity are larger. ***See Appendix PA, Sections 4.8 and 4.9 and Attachment MASS, Section 15.2*** ~~Appendix MASS (Section MASS.15.2 and MASS Attachment 15-6 and Appendix SECOTP2D (Section 2, Governing Equations)~~ for more details.

Chemical retardation of dissolved actinides is conceptualized to occur by sorption onto dolomite grains exposed in diffusive porosity because of the large amount of dolomite present in the Culebra. Chemical retardation increases if diffusive porosity is smaller, because there is a larger volume of rock for sorption. Although clay minerals are present and would sorb actinides in the Culebra, their effects are not included in the conceptual model or specified parameter values. Effective properties for the rock matrix, which is assumed to be homogeneous, and solution chemistry are assumed and are incorporated directly in ~~specification of~~ the ***specified*** parameters for the retardation model (see ***Appendix PA,*** ~~Appendix~~ ***Attachment*** MASS, Section ~~MASS.~~15.2, and ~~Appendix~~ ***Attachment*** PAR, Parameters 49 through 57).

The ~~DOE performance assessment~~***PA*** uses a linear isotherm model to represent the retardation that occurs as dissolved actinides are sorbed onto dolomite. This model uses a single parameter K_d to express a linear relationship between sorbed concentration and liquid concentration. The K_ds used in ~~performance assessment~~***PA*** ~~have been~~ ***were*** determined from experimental data and are conservatively chosen***.*** ~~such that~~ ***Thus,*** the model predictions of sorption are less than or equal to actual sorption expected along the possible flow paths in the Culebra should a release occur (Appendix ***PA, Attachment*** MASS, Section MASS***-***15.2***;*** and ***CCA Appendix*** MASS***,*** Attachment 15-1). Other important parameters in the linear isotherm model are the diffusive porosity and the grain density of the Culebra because these determine the mass of dolomite available on which sorption can occur. Consistent with the assumption of homogeneous rock properties in the conceptual model, K_ds and grain densities are selected, ~~and then~~ applied to the entire transport domain, and ~~are~~ held constant for an entire realization. See ***CCA*** Appendi***x***~~ces~~

SECOTP2D (Section 7, User Interactions, Input and Output Files*)*) and ***Appendix PA, Attachment*** PAR (Parameters 49 through 57) for details of parameter definitions and values.

~~Selection of~~ ***Selecting*** the parameter values required by the SECOTP2D model for physical retardation and chemical retardation is performed in LHS according to the CDFs described in Appendix ***PA, Attachment*** PAR. Important parameter values are summarized in ***Table 6-22***~~6-20~~ and ***Table 6-23***~~6-21~~.

Table *6-22*~~6-20~~. Matrix Distribution Coefficients (K_ds) and Molecular Diffusion Coefficients for Dissolved Actinides in the Culebra

Actinide	K_d (cubic meters per kilogram)			Molecular Diffusion Coefficients (square meters per second)[~~a~~ *1*] Constant
	Maximum	Minimum	Median	
U(IV)	~~2~~*1*0.0	0.*7*~~9~~0	~~10.0~~ ***2.6***	1.53×10^{-10}
U(VI)	0.0~~3~~*2*0	3.0×10^{-5}	***7.7 × 10^-4*** ~~0.015~~	4.26×10^{-10}
Th(IV)	***1***~~2~~0.0	0.~~9~~*7*0	***2.6***~~10.0~~	1.53×10^{-10}
Pu(III)	0.~~5~~*4*0	0.02	***0.09***~~0.26~~	3.00×10^{-10}
Pu(IV)	***1***~~2~~0.0	0.~~9~~*7*0	~~10.0~~***2.6***	1.53×10^{-10}
Am(III)	0.~~5~~*4*0	0.02	0.***09***~~26~~	3.00×10^{-10}

[~~a~~ *1*] See ~~Appendix~~ ***Attachment*** MASS~~, MASS Attachment 15-3~~

Table *6-23* ~~6-21~~. Culebra ~~Actinides Flow and Transport~~ Parameters Required for *SECOTP2D* ~~SECO Codes~~

Parameter (units)	Maximum	Minimum	Median or Constant
Advective porosity (percent)	1.0	0.01	0.10
Diffusive porosity (percent)	25.0	10.0	16.0
Half matrix block length (meters)	0.50	0.05	0.275
Longitudinal dispersivity, αL (meters)	–	–	0
Transverse dispersivity, αT (meters)	–	–	0
Grain density (cubic kilograms per cubic meter)	–	–	2.82
Effective thickness (meters)	–	–	4.0
Fracture tortuosity (unitless)	–	–	1.0
Diffusive tortuosity (unitless)	–	–	0.11

In summary, the conceptual model for dissolved actinide transport includes the following: transport in advective porosity, physical retardation (diffusion) into diffusive porosity, chemical retardation (sorption) in diffusive porosity, homogeneous rock properties, and a linear isotherm to describe the sorption process. Some of the more important parameters are advective porosity, diffusive porosity, tortuosity, matrix block length, molecular diffusion coefficients, K_d, and the grain density of dolomite in the Culebra.

6.4.6.2.2 Transport of Colloidal Actinides in the Culebra

Colloidal particles are subject to many of the same processes that affect dissolved actinides, but because of their size, several additional processes affect them. There are three process differences. Colloidal particles in general are preferentially carried in the center of pore throats by faster-moving fluid, which could cause slightly increased rates of transport compared to dissolved species. Colloidal particles can be filtered from flowing groundwater when they encounter small-aperture features in the pore network. Finally, colloidal particles may undergo different sorption processes than dissolved species.

The primary distinction in the transport behavior of the different colloidal particles is whether particles diffuse into the matrix from fractures. This is controlled by the difference between the size of colloidal particles and the mean pore-throat diameters in the diffusive porosity of the Culebra. Colloidal particles that are smaller than the pore throats can diffuse into the diffusive porosity. Actinide intrinsic colloids and humic materials are small enough for this to occur. The conceptual model for these particles includes the processes of advection, diffusion, and dispersion in the advective porosity; diffusion into diffusive porosity; and sorption of actinides in diffusive porosity. This model is analogous to ~~the model~~ ***that*** specified for dissolved actinides, although the parameter values are different. The conceptual model assumes that other retardation processes (for example, filtration) will not occur for actinide-intrinsic colloids and humic materials.

In contrast, colloidal particles ~~that are~~ larger than pore throats will be excluded from the matrix and will remain in advective porosity. Microbes and mineral fragments are conceptualized as ~~being~~ larger than the mean pore-throat diameter in Culebra diffusive porosity. The conceptual model for these particles includes the processes of advection ~~in advective porosity~~ and filtration by small-aperture features that occur within ~~the~~ advective porosity. See Appendix ***PA, Attachment*** MASS***,*** ~~(~~***CCA*** Section MASS.15.3 ~~and MASS Attachment 15-9)~~ for additional discussion.

Experiments ~~have~~ demonstrated that mineral fragments and microbes are attenuated so effectively by the advective porosity in the Culebra that it was ~~deemed~~ unnecessary to include those colloids in ~~performance assessment~~***PA*** calculations. Under the neutral to slightly basic geochemical conditions expected in the Culebra, humic substances ~~were found to~~ ***did*** not influence the sorption behavior of dissolved actinides. Therefore, actinides associated with humic substances were treated as dissolved species in the ~~performance assessment~~***PA*** calculations. The only actinide-intrinsic colloid found ~~to exist~~ in significant concentrations was ~~the~~ Pu(IV)-polymer. At the WIPP, the total amount of Pu(IV)-polymer introduced to the Culebra was ~~found to be~~ insignificant with respect to the EPA normalized release limit, and so was not included in transport calculations. See Appendix ***PA, Attachment*** SOTERM (Section SOTERM-6***.0***) and Appendix ***PA, Attachment*** MASS (Section MASS-15.3.1) for details. See Appendix ***PA, Attachment*** MASS (Section MASS-15.3.3) for alternative modeling approaches considered.

Indigenous microbes, humics, and mineral fragment colloids in the Culebra may react with ***dissolved*** actinides introduced to the Culebra ~~in dissolved form~~ to create new colloidal actinides. Newly formed actinide-bearing microbial and mineral colloids, however, will be attenuated similarly to colloidal actinides introduced from the repository. Therefore, disregarding the impact of newly formed microbial and mineral fragment colloidal actinides is conservative. Experimental results indicate that humics do not interact with dissolved actinides under Culebra geochemical conditions. Consequently, the quantity of newly formed humic actinides will be insignificant.

6.4.6.2.3 Subsidence Due to Potash Mining

Subsidence effects caused by potash mining are included in this ~~performance assessment~~***PA*** because of specific criteria in the EPA's 40 CFR Part 194. ~~For incorporating~~ ***To incorporate*** the effects of subsidence caused by mining, ~~the DOE~~***PA*** uses the conceptual model provided by ~~the~~ EPA in 40 CFR Part 194 and supporting documents.

The ~~EPA's~~ conceptual model for mining is ~~introduced~~ ***based on information found*** in 40 CFR § 194.32 (b) and (c) and clarified in the Preamble and Background Information. ~~40 CFR §~~***These subparts of Section*** 194.32 (b) and (c) state

> (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 the 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 minerals resources shall be assumed to occur only once during the regulatory time frame.
>
> (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 reasonably 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.

~~40 CFR §~~ ***Section*** 194.32 ~~(b) and (c) state~~ ***establishes assumptions as to*** what gets mined, when it gets mined, and the effects of mining on the disposal system—a conceptual model. Within the disposal system, mineral resources similar in quality and type to those currently ~~being~~ mined outside the disposal system may be mined at an uncertain time in the future. Outside the disposal system, mineral resources reasonably expected to be mined in the near future should be assumed to be mined. These effects are included in analyses of both disturbed and undisturbed performance. Inside the disposal system, whether and when a mining event occurs after the active institutional control period is determined by a probabilistic model. Outside the disposal system, what is reasonably expected to be mined is assumed to be mined by the end of WIPP disposal operations. With respect to consequence analysis, mining affects only the hydraulic conductivity of the ~~of the units of the~~disposal system ***units***.

The DOE has identified areas ~~that are~~ assumed to be mined in a manner consistent with the conceptual model and other guidance presented by the EPA in 40 CFR Part 194. The only natural resource ~~being~~ currently mined near WIPP is potash in the McNutt, and it is the only mineral considered for future mining. ***Appendix PA,*** ~~Appendix~~ ***Attachment TFIELD, Section 9*** ~~MASS (Sections MASS.15.4 and MASS Attachment 15-4) provides a description of~~ ***describes*** the method used to determine the extent of mining in the McNutt both inside and outside the disposal system. This description also presents additional relevant discussion by the EPA on the extent of mining. The extent of mining outside the disposal system used in this ~~performance assessment~~***PA*** is shown in Figure 6-19. It is based on the map of existing leases presented in Chapter 2.0 (Figure ~~2-37~~ ***2-44***), setbacks from existing boreholes, and the presence of ore in the lease (see ***Appendix PA,*** ~~Appendix~~ ***Attachment*** MASS, Section MASS-15.~~4 and MASS Attachment 15-5~~). Inside the disposal system, a region that could be mined in the future is specified based exclusively on the quality and type of ore present. This region was presented in Figure ~~2-38~~ ***2-45*** (see Chapter 2.0).~~ and is reproduced here for convenience as Figure 6-20.~~

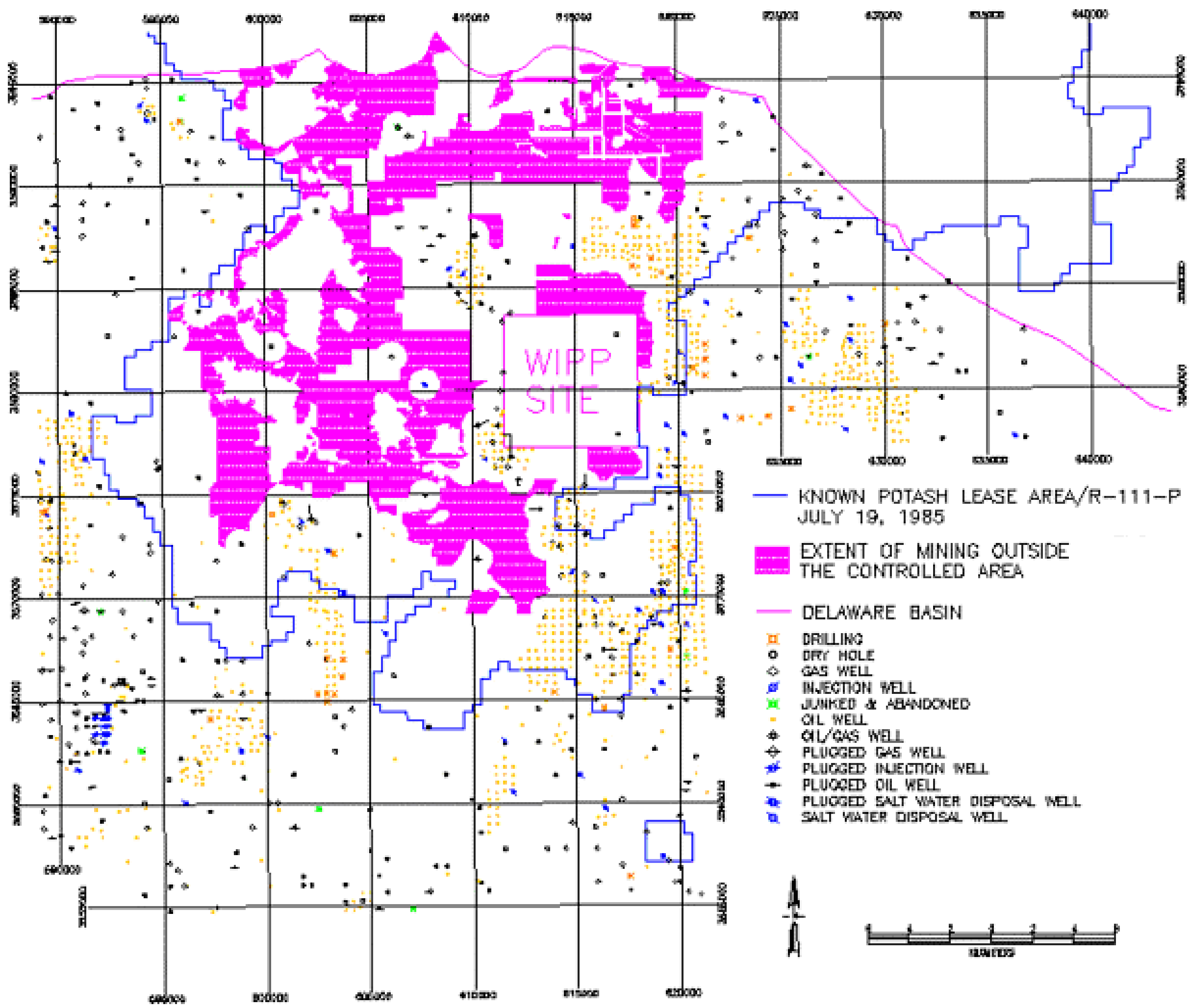


Figure 6-19. Extent of Mining in the McNutt in Undisturbed Performance within *MODFLOW-2000* ~~SECOFL2D~~ Regional Model Domain

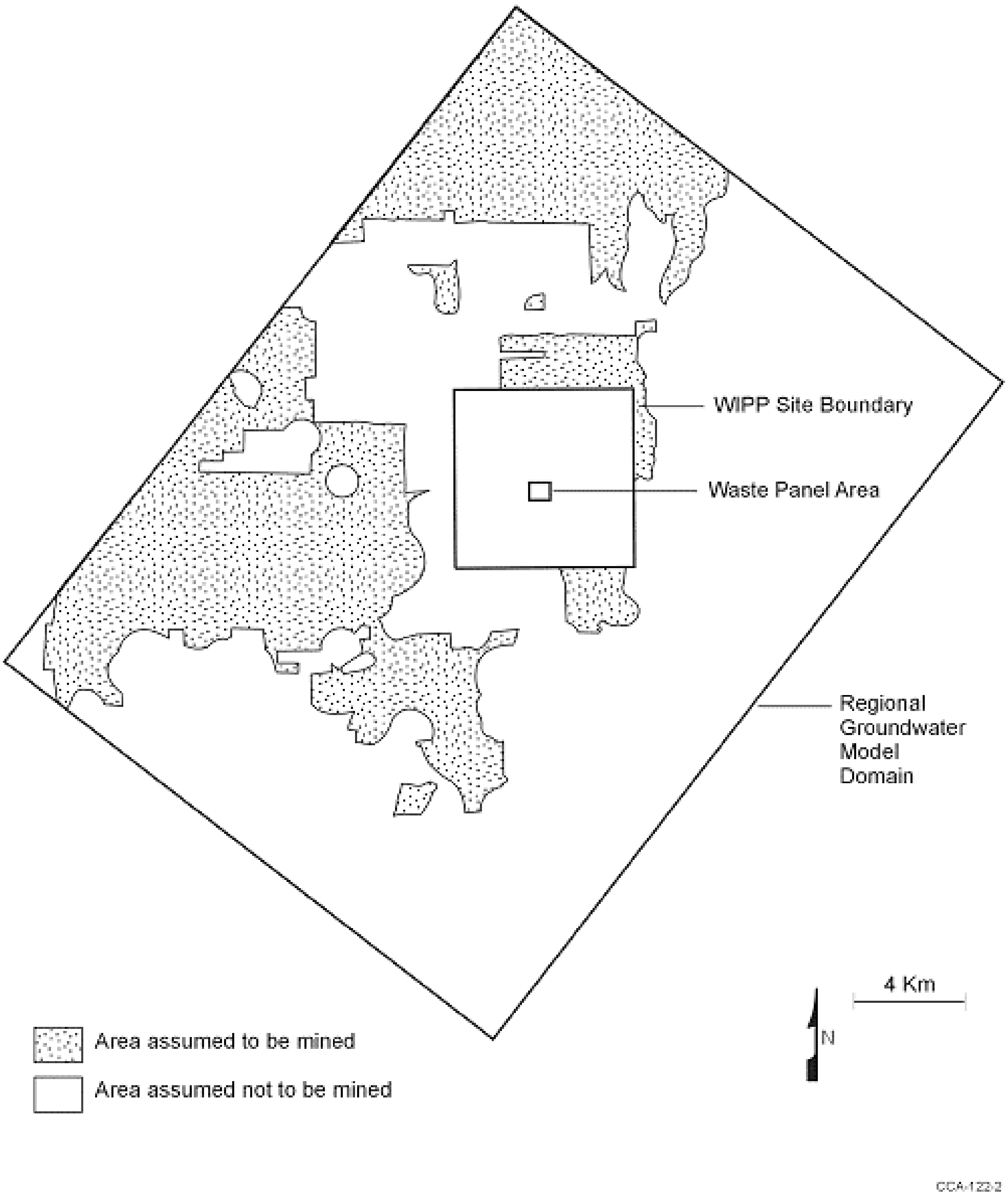
The EPA clarifie~~s~~***d*** its conceptual model on the effects of mining on hydraulic conductivity ~~of the units~~ of the disposal system ***units*** in the Preamble to 40 CFR Part 194 (EPA 1996a, 61 FR 5229). The EPA states

> Some natural resources in the vicinity of WIPP can be extracted by mining. These natural resources lie within the geologic formations found at shallower depths than the tunnels and shafts of the repository and do not lie vertically above the repository. Were mining of these resources to occur, this could alter the hydrologic properties of overlying formations—including the most transmissive layer in the disposal system, the Culebra dolomite—so as to either increase or decrease groundwater travel times to the accessible environment. For the purposes of modeling these hydrologic properties, this change can be well represented by making corresponding changes in the values for the hydraulic conductivity. The Agency has conducted a review of the data and scientific literature discussing the effects mining can induce in the hydrologic properties of a formation. Based on its review of available information, the Agency expects that mining can, in some instances, increase the hydraulic conductivity of overlying formations by as much as a factor of 1,000, although smaller and even negligible changes can also be expected to occur. Thus, the final rule requires DOE to consider the effects of mining in performance assessments. In order to consider the effects of mining in performance assessments, the DOE may use the location-specific values of hydraulic conductivity, established for the different spatial locations within the Culebra dolomite, and treat them as sampled parameters varying between unchanged and increased 1,000-fold relative to the value that would exist in the absence of mining.

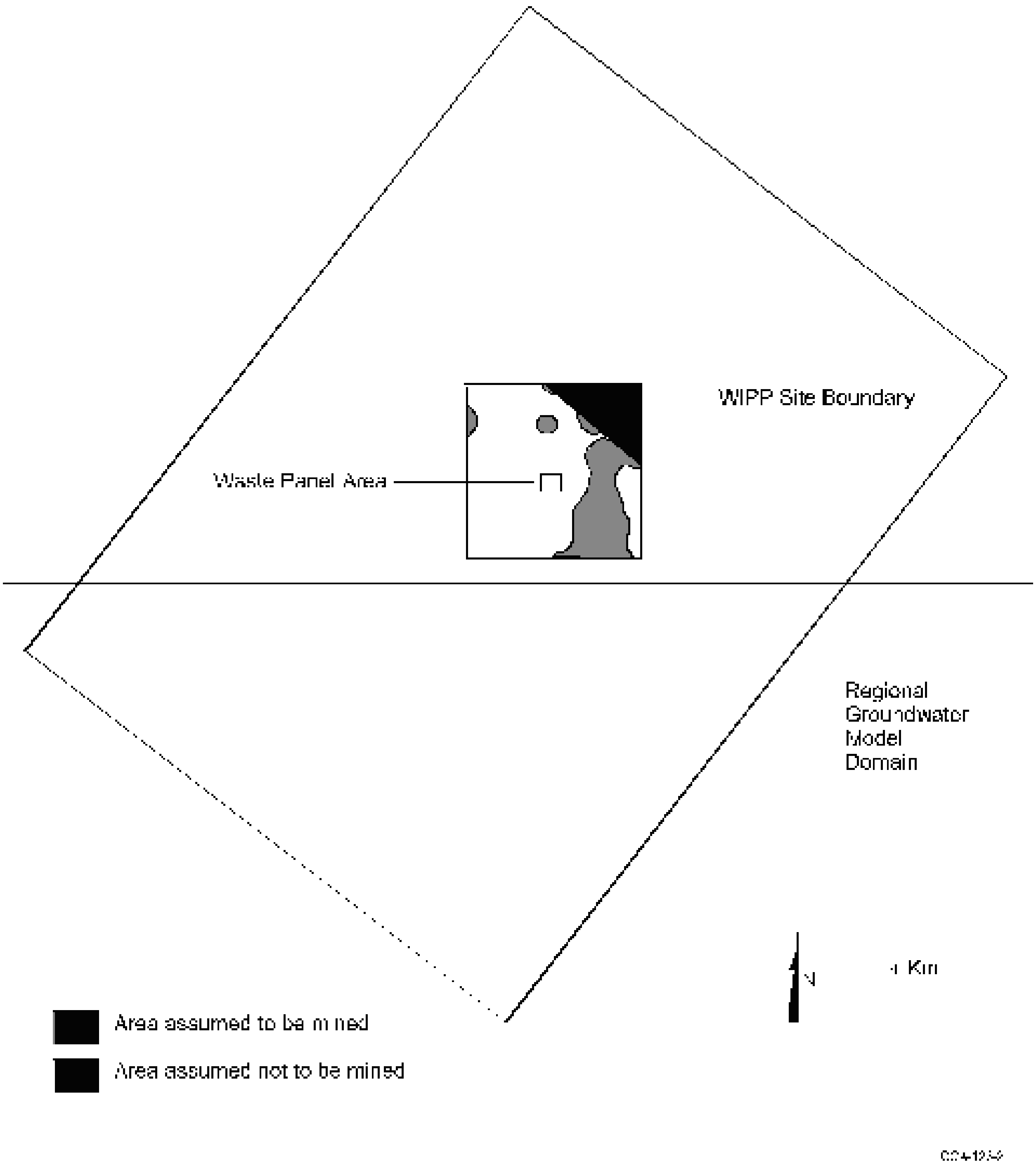
This section adds four important clarifying concepts. First, the EPA ~~has~~ concluded that there are no minerals vertically above the repository similar in quality and type to those currently ~~being~~ extracted elsewhere in the Delaware Basin. Second, the EPA does not draw conclusions about whether mining will increase or decrease groundwater travel times to the accessible environment. Third, it may be assumed that the important effects of change in hydraulic conductivity occur only in the Culebra. Fourth, the spatially variant hydraulic conductivities established in the Culebra by the DOE may be multiplied, where ~~they are~~ impacted by mining, by a factor from 1 to 1,000. The DOE ~~has~~ applied ~~the~~ EPA's guidance regarding hydraulic conductivity to the transmissivity at ~~locations in the~~ Culebra ***locations***.

In using the EPA's conceptual model for mining, the DOE makes assumptions with respect to two topics in order to formulate the mathematical model. The angle of draw is a parameter necessary to translate the area mined in the McNutt to the area affected in the Culebra. In its Background Information Document for 40 CFR Part 194, the EPA discusses the possible range in the value of angle of draw (EPA 1996b, 9-36). The DOE ~~has~~ examined the Background Information for 40 CFR Part 194 (see EPA 1996b, 9-47) and concluded that ~~an~~ ***a 45°*** angle of draw ~~of 45°~~ is the value most consistent with the EPA's discussions and calculations. Second, the Agency does not specify a distribution to the multiplicative factor. As discussed in ***Appendix PA,*** ~~Appendix~~ ***Attachment*** PAR (Parameter ***46*** ~~34~~), the DOE has assigned a uniform distribution to this variable. As discussed in the introduction to ***Appendix PA,*** ~~Appendix~~ ***Attachment*** PAR, a uniform distribution is appropriate when only lower and upper bounds of the range are known.

Applying the angle of draw to the mined areas presented in ~~Figure 6-19 and 6-20~~ ***6-20 and 6-21*** makes the area impacted in the Culebra larger than the area actually mined in the McNutt. The area in the Culebra impacted by mining is shown in ~~Figure 6-21~~ ***Figure 6-20*** for outside the controlled area, and in ~~Figure 6-22~~ ***Figure 6-21*** for inside and outside the controlled area. These figures are plotted on the regional domain of the ~~SECOFL2D~~ ***MODFLOW-2000*** model, which ~~is~~

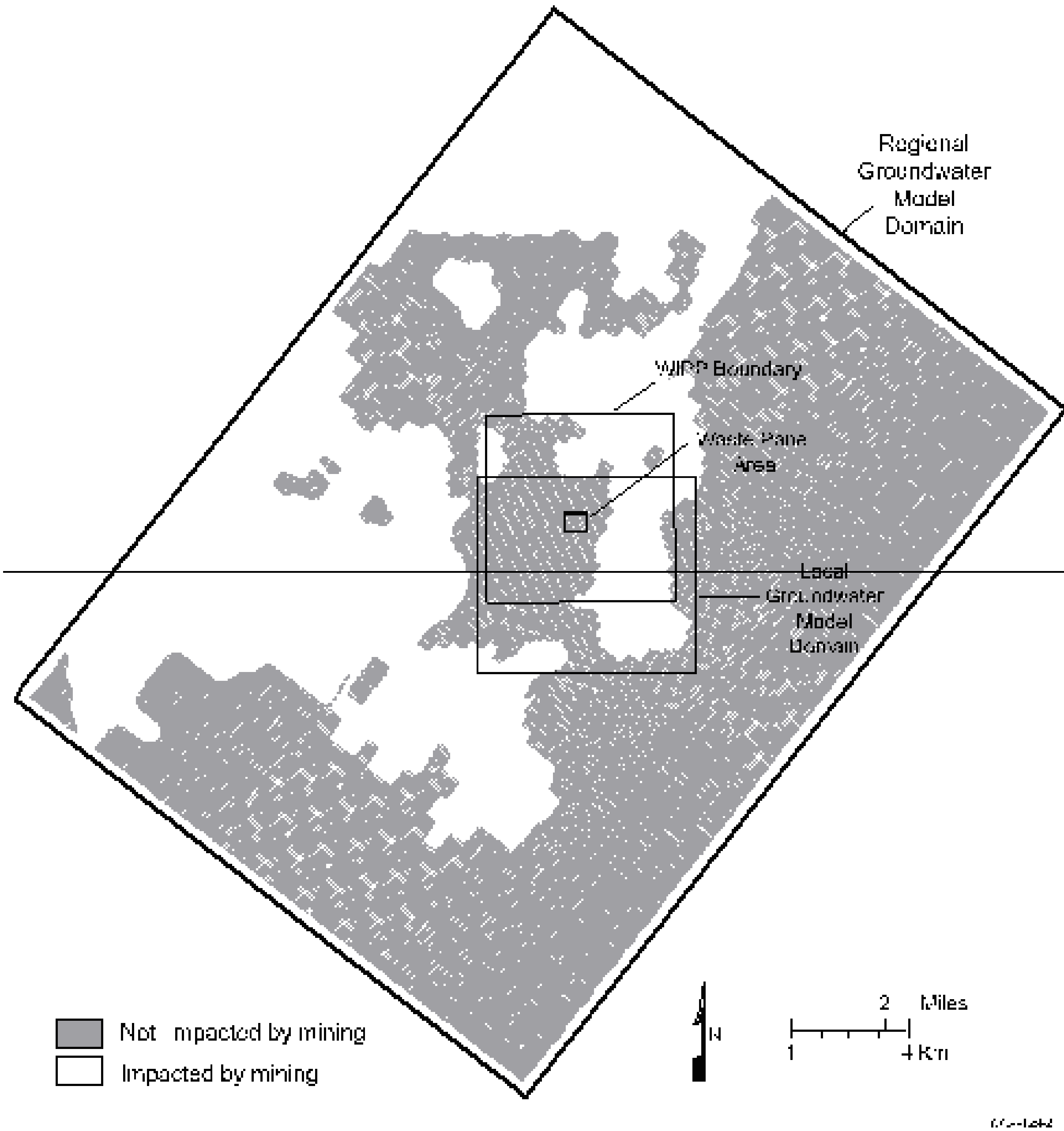


~~Figure 6-19. Extent of Future Mining in the McNutt the Controlled Area Considered in Disturbed Performance~~



~~**Figure 6-20. Extent of Future Mining in the McNutt within the Controlled Area Considered in Disturbed Performance**~~

~~Figure 6-21. Extent of Impacted Area in the Culebra from Mining In the McNutt Outside the Controlled Area for Undisturbed Performance~~



~~**Figure 6-22. Extent of Impacted Area in the Culebra for Disturbed Performance if Mining In the McNutt Occurs in the Future Within the Controlled Area**~~

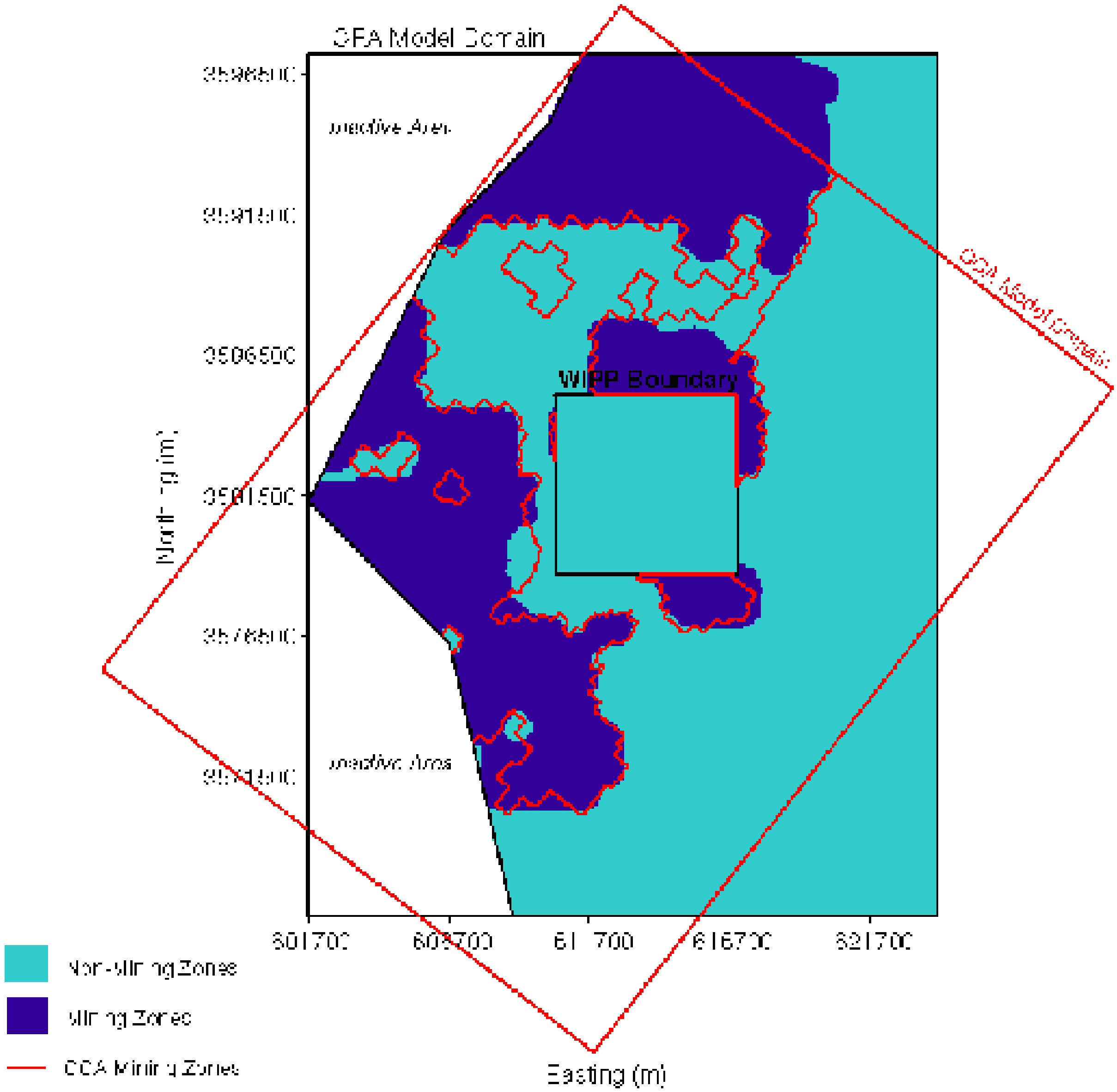


Figure 6-20. Extent of Impacted Area in the Culebra from Mining in the McNutt Potash Zone of the Salado Outside the Controlled Area for Undisturbed Performance

~~used to~~ calculate***d*** the effects of subsidence caused by mining on flow directions and rates in ~~performance assessment~~***PA***.

The effects of mining outside the disposal system are included in the undisturbed performance scenario, and, therefore, the effects ~~of this mining~~ are included in all scenarios. In other words, all calculations of transport in the Culebra include the effects of mining outside the controlled area. This is the undisturbed mining case because mining within the controlled area has not occurred.

These effects are incorporated by multiplying location-specific values in the transmissivity field in the area labeled "***Mining Zones*** ~~Impacted by Mining~~" in Figure 6-21 by a factor (mining

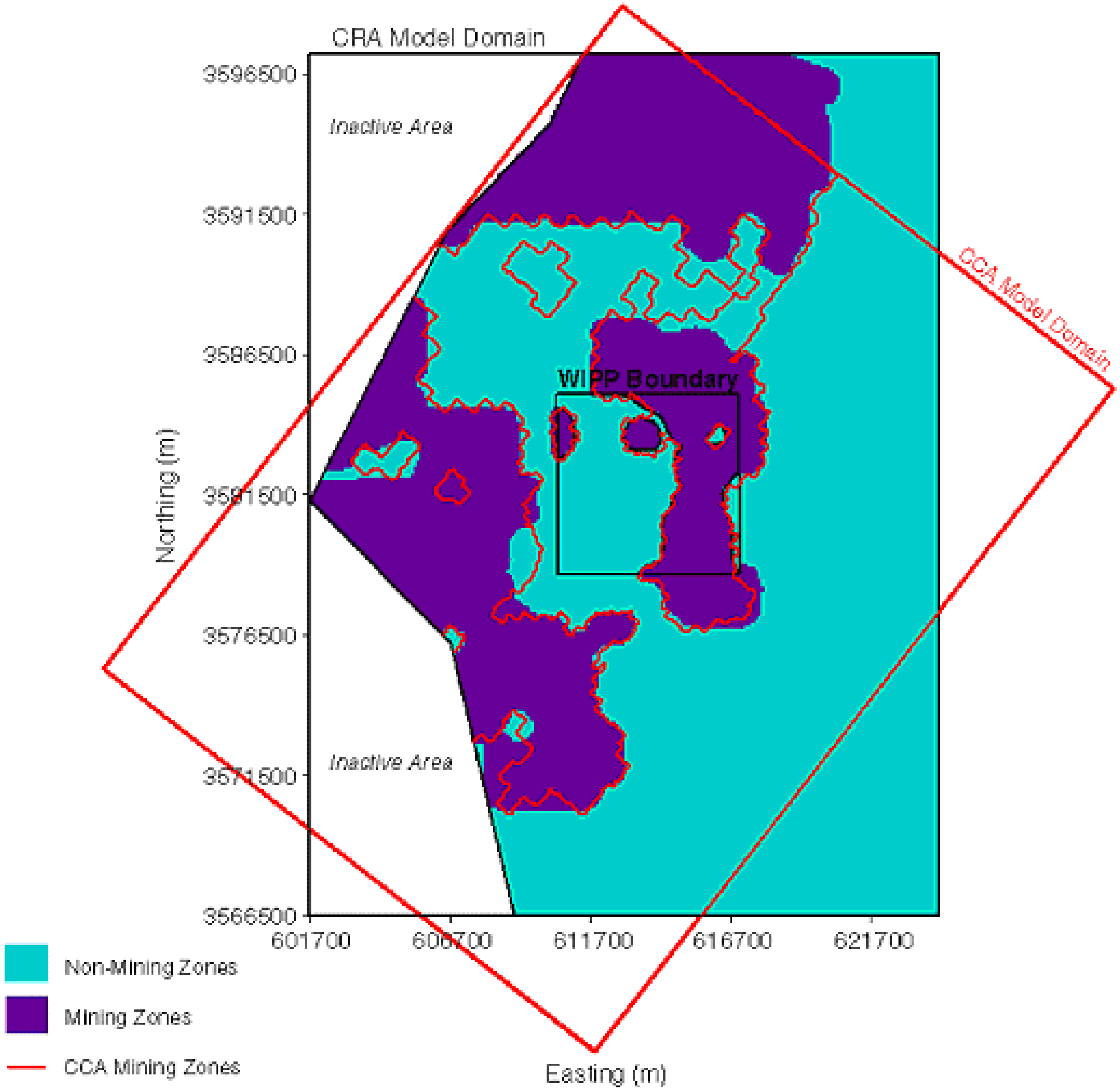


Figure 6-21. Extent of Impacted Area in the Culebra for Disturbed Performance if Mining in the McNutt Potash Zone of the Salado Occurs in the Future Within and Outside of the Controlled Area

multiplier) between 1 and 1,000 that is randomly sampled in LHS. The same factor is applied to all affected nodal blocks. In every vector of the LHS, the steady-state flow fields used in the 10,000-year transport simulation incorporate this change to the transmissivity field. These simulations, followed by a transport simulation (as discussed in preceding sections), develop reference conditions for the transport of actinides in the Culebra in the undisturbed mining case.

If mining occurs within the controlled area, an area of the Culebra inside and outside the disposal system is affected. This is the disturbed mining case. To evaluate the impact of disturbed mining, a second simulation of Culebra flow directions and rates is executed ~~on the regional and local domains~~. In this second simulation, the affected location-specific values in the transmissivity field within the controlled area are multiplied by the same mining multiplier used for the undisturbed mining case outside the controlled area. These simulations, followed by a transport simulation (as discussed in preceding sections), develop reference conditions (see Section 6.4.11) for ~~the~~ transport***ing*** ~~of~~ actinides following mining inside the controlled area.

The implementation of the EPA's probability model for future mining is presented in Section 6.4.12.8. A discussion of how the reference simulations for the undisturbed and disturbed mining cases are used in CCDF construction is presented in Section 6.4.13.

6.4.6.3 The Tamarisk

The Tamarisk (***Row 27*** ~~Region 16~~ in Figures 6-14 and 6-15) rests between the more transmissive Culebra and Magenta. An in-situ hydraulic test determined that the transmissivity of the Tamarisk is lower than the transmissivity of the ***Los Medaños*** ~~unnamed lower member~~ (see Section 2.2.1.4.1.3). This low transmissivity is consistent with expectations because of its anhydrite, gypsum, and clay composition (see Section 2.1.3.5.3). In ~~performance assessment~~***PA***, this member is treated as impermeable. This may cause ~~an~~ increase***d*** ~~in~~ flow through the adjacent Culebra and Magenta. This treatment is considered conservative in that allowing flow from the intrusion borehole or shaft into the Tamarisk would, if anything, decrease flow into the Culebra, which would ~~tend to~~ reduce the consequence of radionuclide release to the Rustler. In ~~performance assessment~~***PA***, the thickness of the Tamarisk is assumed to be 24.8 m (81.4 ft) and its permeability is effectively zero (Appendix ***PA, Attachment*** PAR~~, Table PAR-29~~).

6.4.6.4 The Magenta

The Magenta is described in Sections 2.1.3.5.4 and 2.2.1.4.1.4 and is shown as ***Row 28*** ~~Region 15~~ in Figures 6-14 and 6-15. Transport of actinides through the Magenta to the accessible environment is not modeled. The assumption that no releases will occur from the Magenta is based on the hydraulic test results from wells on the WIPP site (Beauheim 1987, 110-118)***,*** ~~that~~ ***which*** indicate that the Magenta is a porous medium with no hydraulically significant fractures (in contrast to the Culebra), and that its conductivity is lower than that of the Culebra. Early numerical simulations of flow and transport in the Magenta suggested much slower transport than in the Culebra (Barr et al. 1983, 26-27). Therefore, no radionuclides entering the Magenta will reach the accessible environment boundary within the 10,000-year time frame. Accordingly, the BRAGFLO model geometry reasonably approximates the effects of Magenta flow. The Magenta permeability is chosen conservatively as the lowest of measured values near the center of the WIPP site, in order to yield a lower reasonable amount of brine (and radionuclide) storage within the Magenta while continuing to yield an upper bounding flow into the Culebra. The volumes of brine and radionuclides ~~calculated~~ to be stored in the Magenta are tracked and documented, however. Magenta parameter values are summarized in ***Table 6-24*** ~~Table 6-22~~ and are described in more detail in Appendix ***PA, Attachment*** PAR ~~(Table PAR-28)~~.

6.4.6.5 The Forty-niner

In evaluations of radionuclide transport, flow in the Forty-niner is considered insignificant because of its low transmissivity (see Section 2.2.1.4.1.5). As with the Tamarisk and ***Los Medaños*** ~~unnamed lower members~~, the Forty-niner is assigned a permeability of effectively zero in ~~performance assessment~~***PA*** (Appendix ***PA, Attachment*** PAR~~, Table PAR-27~~). This treatment is considered conservative ~~in that~~ ***because*** allowing flow from the intrusion borehole or shaft into the Forty-niner would, if anything, decrease flow into the Culebra, which would ~~tend to~~ reduce the consequence of radionuclide release to the Rustler. Its modeled thickness is 17.3 m (56.8 ft). It is shown as ***Row 29*** ~~Region 14~~ in Figures 6-14 and 6-15.

6.4.6.6 Dewey Lake

Release of actinides to the accessible environment from transport in the Dewey Lake is assumed not to occur even if contaminated brine reaches the unit, because the sorptive capacity of this unit appears large. This assumption is based on an analysis (Wallace et al. 1995) that demonstrated that the potential sorption capacity of the Dewey Lake is sufficient to prevent releases for 10,000 years. This analysis consisted of (1) a literature review ~~of~~ ***on the*** sorptive capacity of redbeds and (2) an estimate of the minimum sorption required to prevent ~~release of~~ actinide~~s~~ ***releases*** that enter the Dewey Lake to the accessible environment in 10,000 years.

Comparison of the sorption values for the Dewey Lake analogues established by literature review with the minimum sorption required to prevent release indicates that the likely sorptive capacity of the Dewey Lake is orders of magnitude greater than ~~would likely be~~ required to prevent release. Therefore, the DOE assumes that chemical retardation occurring in the Dewey Lake will prevent release within 10,000 years of any actinides that might enter it. Geological and hydrological information on the Dewey Lake is presented in Sections 2.1.3.6 and 2.2.1.4.2, respectively. Dewey Lake parameter values are summarized in ***Table 6-25***~~Table 6-23~~ (see also Appendix ***PA, Attachment*** PAR~~, Table PAR-26~~). The Dewey Lake is shown ~~as Region 13~~ in Figures 6-14 and 6-15.

Table *6-24*~~6-22~~. Model Parameter Values for the Magenta

Parameter (units)	***Minimum***	***Maximum***	~~Value~~ ***Mean or Constant***
Permeability (square meters)			6.31×10^{-16}
Effective porosity (percent)	***2.7***	***25.2***	13.8
Rock compressibility (1/pascals)~~[a]~~ ***[1]***	***1.16×10^{-10}***	***4.55×10^{-10}***	2.64×10^{-10}
Threshold pressure, P_t (pascals)~~[b]~~ ***[2]***			5.06×10^{4} (~~5~~)
Residual brine saturation, S_{br} (unitless)			0.084
Residual gas saturation, S_{gr} (unitless)			0.077
Pore distribution parameter, λ (unitless)			0.644
Maximum capillary pressure			10^8
Thickness (meters)			8.5
Initial pressure (pascals)			9.47×10^5

~~a~~ ***1*** Pore compressibility = rock compressibility/effective porosity.

~~b~~ ***2*** Threshold Pressure (P_t) determined from the relationship: $PCT\_A \cdot k^{PCT\_EXP}$, where PCT_A and PCT_EXP are constants and k is the permeability.

Table *6-25*~~6-23~~. Dewey Lake Parameters for the BRAGFLO Model

Parameter (units)	***Minimum***	***Maximum***	~~**Value**~~ ***Mean or Constant***
Permeability (square meters)			***5.01×10^{-17}***
Effective porosity (percent)	***3.5***	***24.8***	14.3
Rock compressibility (1/pascals)[~~a~~ *1*]			10^{-8}
Threshold pressure, P_t (pascals)[~~b~~ *2*]			0
Residual brine saturation, S_{br} (unitless)			0.084
Residual gas saturation, S_{gr} (unitless)			0.077
Pore distribution parameter, λ (unitless)			0.644
Maximum capillary pressure (pascals)			10^{8}
Thickness (meters)			149.3
Initial pressure (below water table at 980 m, 43.3 m below top of formation) (pascals)			hydrostatic
Initial pressure, 20% liquid saturation above water table (atmospheres)			1

[~~a~~ *1*] Pore compressibility = rock compressibility/effective porosity.

[~~b~~ *3*] Threshold pressure (P_t) determined from the relationship: $PCT\_A \cdot k^{PCT\_EXP}$, where PCT_A and PCT_EXP are constants and k is the permeability.

6.4.6.7 Supra-Dewey Lake Units

The units overlying the Dewey Lake are discussed in Sections 2.1.3.7 through 2.1.3.10 and are shown as ***Rows 32 and 33*** ~~Region 12~~ in Figures 6-14 and 6-15. Because these units are thin and predominantly unsaturated at the WIPP site, brine that might enter from the borehole (assuming brine can reach this elevation) is assumed to flow downward to the Dewey Lake, where any actinides will be sorbed. These units are included in BRAGFLO, however, and the possibility of actinide transport into them from a borehole is considered in the ~~performance assessment~~***PA***. Actinide transport within the Supra-Dewey Lake units is not modeled, and it is assumed that there can be no actinide release to the accessible environment through these units. For ~~performance assessment~~***PA***, the units overlying the Dewey Lake are represented as a single hydrostratigraphic unit whose parameters are shown in ***Table 6-26*** ~~Table 6-24~~.

6.4.7 The Intrusion Borehole

In accordance with the requirements of 40 CFR § 194.33(b)(1), ~~the~~ DOE models consequences of inadvertent and intermittent intrusion into the repository during drilling for natural resources as the most severe human intrusion scenario that ~~may~~ ***could*** affect long-term performance of the disposal system. This section discusses the conceptual models used for drilling (particulate release during drilling, direct brine release during drilling, and long-term brine flow) and ~~provides references~~ ***refers*** to appropriate discussions of numerical modeling codes.

This section does not address the likelihood that inadvertent human intrusion will occur. ~~As discussed in Chapter 7.3.4, the DOE believes passive institutional controls will be effective in reducing the likelihood of intrusion (see Appendix EPIC); however, regulatory guidance requires~~

Table *6-26*~~6-24~~. Supra-Dewey Lake Unit Parameters for the BRAGFLO Model

Parameter (units)	Value
Permeability (square meters)	10^{-10}
Effective porosity (percent)	17.5
Rock compressibility (1/pascals)~~[a]~~[1]	5.71×10^{-8}
Threshold pressure, P_t (pascals)~~[b]~~[2]	0
Residual brine saturation, S_{br} (unitless)	0.084
Residual gas saturation, S_{gr} (unitless)	0.077
Pore distribution parameter, λ (unitless)	0.644
Maximum capillary pressure (pascals)	10^{8}
Thickness (meters)	15.76
Initial pressure, 8.36% liquid saturation (atmospheres)	1

~~[a]~~[1] Pore compressibility = rock compressibility/effective porosity.

~~[b]~~[2] Threshold pressure (P_t) determined from the relationship: $PCT\_A \cdot k^{PCT\_EXP}$, where PCT_A and PCT_EXP are constants and k is the permeability.

~~consideration of a nonzero probability of intrusion (40 CFR § 194.43[c]).~~ The DOE's treatment of the probability of inadvertent human intrusion is discussed in Section 6.4.12.

Human intrusion scenarios require simulating penetration of an intrusion borehole into the waste disposal region. There are two effects associated with drilling: releases from the drilling itself and possible releases ~~because of~~ ***from*** the long-term effects on fluid flow in the disposal system after the borehole casing and plugs have degraded. Both types of releases are estimated for two different types of intrusions: those that intersect pressurized brine in the Castile (E1 events; see Section 6.3.2.2.2), and those that do not (E2 events: see Section 6.3.2.2.1).

6.4.7.1 Releases During Drilling

Consistent with the criterion of 40 CFR § 194.33(c)(1), releases that may occur during and immediately following the drilling event are modeled ~~under the assumption~~ ***assuming*** that future drilling practices will be the same as ~~those of the~~ ***at*** present (see ***CCA*** Appendix DEL, Sections DEL.5***,*** ~~and~~ DEL.6 ***and Appendix DATA, Section 2.0 and DATA, Attachment A***, for a complete description of ***historical and*** present drilling practices). ~~Figure 6-23~~ ***Figure 6-22*** shows a schematic representation of a standard rotary drilling operation inadvertently penetrating the repository. A drill bit is attached to the bottom of a string of steel pipe, the lowest segments of which are reinforced collars. The drill bit, collars, and pipe are collectively referred to as the drill string. As the drill string rotates, liquid, referred to as drilling mud, is pumped down the interior of the pipe and out through the bit. The drilling fluid cools and lubricates the bit and then returns to the surface outside the pipe in the annulus between the pipe and the borehole wall.

During its return flow, the mud carries the cuttings to the surface where they settle out in a mud pit. The mud is typically a water-based brine that is weighted with additives to maintain a hydrostatic pressure in the borehole equal to or greater than the normally anticipated fluid pressures in the formations being drilled. Salt-saturated brines are generally used in evaporites

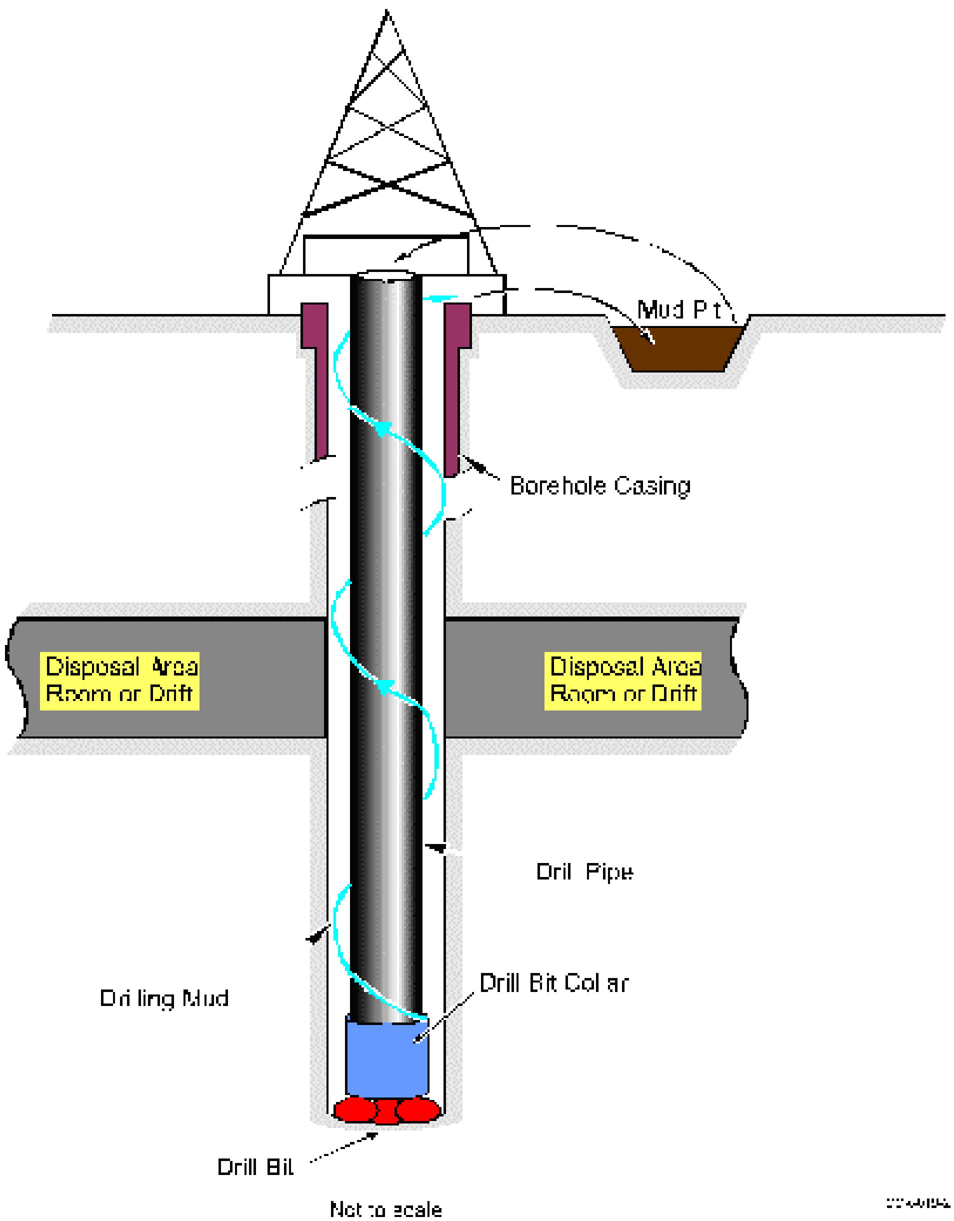


Figure *6-22*~~6-23~~. Schematic Representation of a Rotary Drilling Operation Penetrating the Repository

to prevent dissolution of the formation. Steel casing is installed in boreholes before entering the salt section to protect the near-surface units from contamination with fluids from deeper units and, after drilling through the salt section, to prevent hole closure on the drill string and subsequent in-hole hardware.

If a rotary drill bit penetrates the waste, radionuclides may be brought to the surface by four means. First, some quantity of cuttings~~, which~~ ***that*** contain material intersected by the drill bit will be brought to the surface. Second, cavings, which contain material eroded from the borehole wall by the circulating drill fluid, may also be brought to the surface by the circulating drilling mud. Third, releases of radionuclides may occur if the repository contains fluids at pressures higher than the pressure exerted by the drilling fluid. Spalling of waste material into the borehole may occur if high-pressure gas flows into the borehole. Brine, as well as gas, may enter the borehole from the repository if the driller is unable to control the pressure within the well or ~~if the driller~~ chooses not to control the pressure. The brine may flow to the surface, and if it has been in contact with waste, it may contain dissolved or suspended radionuclides.

Releases of particulate waste material (that is, cuttings, cavings, and spallings) are modeled using the CUTTINGS_S ***and DRSPALL*** code***s***, as described in Section 6.4.11 and Appendix ***PA, Sections PA-4.5 and PA-4.6*** ~~CUTTINGS.~~***,*** ~~Appendix~~ ***Attachment*** MASS (Section ~~MASS.~~16.1) discusses the conceptual basis for the model. As discussed in Section 6.4.12.4, cuttings and cavings are calculated separately for CH-TRU and RH-TRU waste, with distinct waste streams considered. Spallings are calculated as homogeneous waste obtained by averaging over all CH-TRU waste. For all releases during drilling, appropriate corrections are made for radioactive decay. Releases of dissolved or suspended radionuclides contained in brine are modeled using the BRAGFLO and PANEL codes, as described in the next section. Casing is assumed to be intact through the Rustler and overlying units during drilling, and there is assumed to be no communication between the borehole and those units. For all direct releases, actinides that enter the borehole are conservatively assumed to reach the surface.

6.4.7.1.1 Direct Brine Release During Drilling

Direct brine release refers to the possibility that brine containing actinides may flow from the waste panels up a borehole to the surface during drilling (***Appendix PA, Section PA-4.7 and*** ~~Appendix~~ ***Attachment*** MASS, Section ~~MASS.~~16.2). It is conceptualized that direct brine release to the surface will not occur every time a borehole penetrates the waste panels but rather that it can occur only when two conditions are met. The first condition is the presence of mobile brine in the waste panels. Because of brine consumption by corrosion and low initial saturation, it is possible for liquid saturations below the residual saturation to exist in the repository, in which case direct brine release cannot occur. The second condition is ***that*** the pressure in the waste panels must be greater than the pressure at the base of the ~~column of~~ drilling mud ***column***. Drillers in the Delaware Basin use a salt-saturated mud with a specific gravity of about 1.23 while drilling through the Salado. This corresponds to a pressure of approximately 8 megapascals at the repository horizon (see Appendix ***PA, Attachment*** MASS, Section ~~MASS.~~16.2~~,~~ ***and CCA Appendix*** ~~and~~ MASS, Attachment 16-2). If fluid in the waste panels is below this pressure, no direct brine release during drilling can occur because liquid flow in the repository ~~will be~~ ***is*** away from the borehole.

In the conceptual model, resolution of the details of flow near the borehole is considered important, as the changing physical conditions over the short duration of this flow can significantly impact estimates of the total volume released. It is not assumed that a direct brine release would be noticed by the driller (EPA 1996a, 61 FR 5230). Also important to the conceptual model is how long direct brine release occurs. There are several ways in which the direct brine release could be stopped. A driller might detect higher flow rate to the mud pit and take action to mitigate consequences. Alternatively, direct brine release will stop when the driller cases the hole after reaching the base of the salt section. As discussed in Appendix ***PA, Section PA-4.7*** ~~MASS (MASS Attachment 16-2)~~ and ***CCA*** Appendix DEL (Section 7.5), the DOE assumes that for low volumes of fluid flow, the borehole will be controlled and cased within 72 hours after ~~the penetration of~~ ***penetrating*** the repository. In all cases, all fluid flow to the surface during drilling is assumed to cease within 11 days after ~~penetration of~~ ***penetrating*** the repository.

In the conceptual model for direct brine release, several other assumptions are ~~made that~~ relate***d*** to other conceptual models. The processes of direct solids release from cuttings, cavings, spall, and direct brine release are treated separately, although the direct brine release model does account for the effects of solids removal (spall) on fluid flow near the well bore. Direct brine release will affect the pressure and saturation in the repository. However, it is assumed that these effects are negligible over the long term because of their transient and local nature; ~~and~~ ***thus,*** they are not accounted for in long-term (10,000-year) BRAGFLO disposal system calculations. This assumption simplifies modeling because it allows detailed consideration of direct brine release over a short time period, without having to couple the results of these calculations back into the disposal system simulations.

The area over which fluid flow can occur during direct brine release is assumed to be the rooms and drifts of waste panels, the DRZ, room pillars, and panel closures. Because local-scale, short-duration flow is important, the geometry of the waste panels is considered important and is represented in the model. It is assumed that the flow interactions with the Salado other than the DRZ are ~~not~~ ***un***important during direct brine release. For this model, pillars are arbitrarily assumed to have the properties of the DRZ rather than intact halite, although in reality their properties are probably like a DRZ at their edge and ~~like~~ intact halite in their core. Since the DRZ permeability is greater than the permeability of intact halite, this assumption is conservative. A two-dimensional geometry is used parallel to the repository horizon, with a 1 degree dip from north to south. The geometry of the grid used is shown in ~~Figure 6-24~~ ***Figure 6-23***.

The BRAGFLO code is used to calculate direct brine release; ~~and~~ the mathematical and computational model is called the BRAGFLO direct brine release ~~(BRAGFLO_DBR)~~ model (Appendix ***PA, Section PA-4.7*** ~~MASS, Section MASS.16.2 and MASS Attachment 16-2~~). The initial and boundary conditions for this model are derived from the corresponding BRAGFLO disposal system simulation through several codes, including CUTTINGS_S. Some of the parameters derived from the BRAGFLO disposal system model are permeabilities, porosities, two-phase flow properties, and the height of the waste region. Initial saturations and pressures in the BRAGFLO direct brine release model are mapped from the BRAGFLO disposal system model. Other parameters used in the BRAGFLO direct brine release models are consistent with those used in the BRAGFLO disposal system model (Appendix ***PA, Section PA-4.7).*** ~~MASS, Section MASS.16.2 and MASS Attachment 16-2, 3-5).~~

It is possible that a direct brine release could occur from a panel ~~that is~~ connected by a previously-drilled, abandoned borehole to a brine reservoir in the Castile. If this ~~were to~~ happen***ed***, flow directly between the two boreholes, analogous to the E1E2 scenario for long-term performance, ~~may~~ ***might*** affect the estimate of the total brine released. The direct brine release for this possibility is calculated by BRAGFLO ***(direct brine release)*** ~~_DBR~~ by placing a

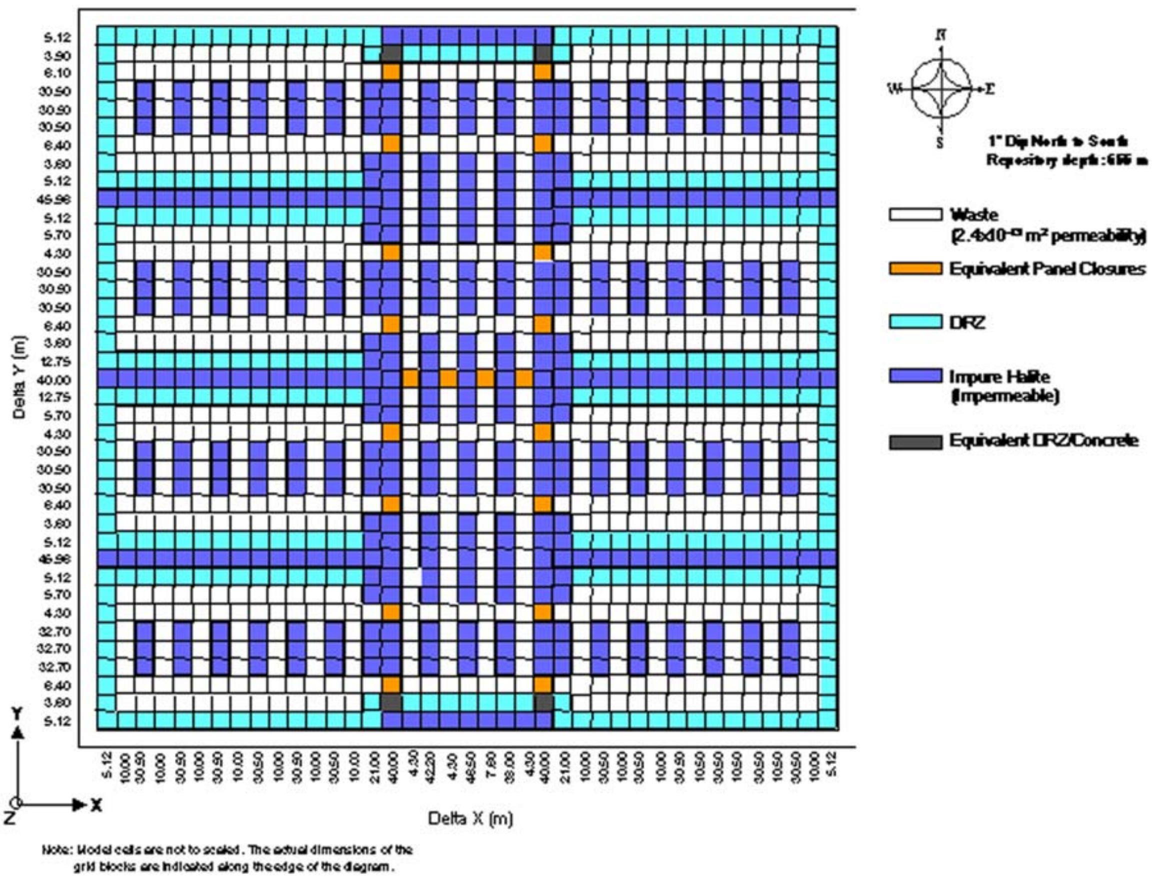


Figure *6-23*~~6-24~~. Repository-Scale Horizontal BRAGFLO Mesh Used for Direct Brine Release Calculations

constant-pressure, flowing injection well as a boundary condition in the model. The locations ~~used for~~ ***of*** these boreholes are shown in ~~Figure 6-24~~ ***Figure 6-23***. It is assumed that a direct brine release from a panel ~~that has~~ ***with*** a previously-drilled, abandoned borehole of the E2 type is ~~not~~ ***un***affected by the presence of the other borehole. Thus, reference direct brine release conditions are calculated for previously unintruded and E2-intruded panels, and for previously-intruded E1 panels. Details about the properties assigned to the flowing-well boundary condition are discussed in ***Appendix PA, Section PA-4.7.*** ~~Appendix MASS (Section MASS.16.2 and MASS Attachment 16-2, Appendix A).~~ Details about how the consequences of direct brine releases from other possible combinations of boreholes are accounted for in the CCDF are discussed in Section 6.4.13**.**

A borehole could penetrate the repository anywhere. For simplification, the BRAGFLO direct brine release model assumes that ~~calculation of~~ ***calculating*** direct brine release from several defined locations provides meaningful reference results for the possible variation in release because of location. The locations of boreholes from which representative results are calculated are indicated in ~~Figure 6-24~~ ***Figure 6-23***. In construction of a CCDF (see Section 6.4.13), the direct brine release associated with a borehole whose position is randomly selected is correlated with the reference release most consistent with the geometry near the location of the random borehole.

Accurate representation of the flow into the borehole is ~~considered~~ important in the BRAGFLO direct brine release model. Accordingly, a number of mathematical methods that are not used to calculate long-term releases are applied to the conditions in the borehole for ~~calculation of~~ ***calculating*** direct brine releases. The methods used appear in Appendix ***PA, Section PA-4.7.*** ~~MASS (Section MASS.16.2 and MASS Attachment 16-2).~~

6.4.7.2 Long-Term Releases Following Drilling

Long-term releases to the ground surface or into groundwater in the Rustler or overlying units may occur after the hole has been plugged and abandoned (Appendix ***PA, Attachment*** MASS, Section ~~MASS.~~16.3). As required by regulation, the plugging and abandonment of future boreholes are assumed to be "consistent with practices in the Delaware Basin at the time a compliance application is prepared" [40 CFR § 194.33(c)(1)]. ~~Detailed examination of~~ ***Examining*** current practice***s*** in the Delaware Basin indicates that all boreholes abandoned recently are plugged to meet state and federal regulatory requirements protecting groundwater and natural resources (see ***Appendix DATA, Section DATA-2.0 and Attachment A; CCA*** Appendix DEL, Sections DEL.5.5 and DEL.6***]***; Appendix ***PA, Attachment*** MASS, Section MASS***-***16.3 ~~and MASS Attachment 16-3~~). These plugs will ~~be~~ effective***ly*** ~~in~~ prevent~~ing~~ flow in abandoned boreholes for some period of time after emplacement. However, some plugs may fail and radionuclides may be transported in brine flowing up the borehole.

Borehole plug configurations used today in the Delaware Basin vary based on the local stratigraphy encountered in the hole, its total depth, and the types of fluids present. All holes are plugged with some combination of solid concrete plugs isolating different fluid-bearing horizons from each other and from the ground surface. As discussed in detail in Appendix ***PA, Attachment*** MASS (Section ~~MASS.~~16.3***), SNL (2003),*** ~~and MASS Attachment 16-1~~) and ***CCA*** Appendix DEL (DEL Attachment 7), six different plug configurations are identified that are potentially relevant to future borehole abandonment practice at the WIPP. As discussed in Appendix ***PA, Attachment*** MASS (Section ~~MASS.~~16.3.3***)*** and ***SNL (2003)*** ~~MASS Attachment 16-3, Section 2.0)~~, these six plug configurations can be approximated for ~~performance assessment~~***PA*** by three conceptual plugging patterns. The three plugging configurations addressed in the ~~performance assessment~~***PA*** are described in the following section. Probabilities of occurrence for each of these three plugging configurations are discussed in Section 6.4.12.7. Parameters used to describe the borehole and its plugs are summarized in ***Table 6-27***~~Table 6-25~~.

6.4.7.2.1 Continuous Concrete Plug through the Salado and Castile

In this configuration, a continuous concrete plug is assumed to exist throughout the Salado and Castile (Appendix ***PA, Attachment*** MASS, Section ~~MASS.~~16.3 and ***SNL (2003)***~~MASS Attachment 16-3, Figure 1)~~. Such a plug could be installed in keeping with current regulatory requirements of the New Mexico Oil Conservation Division Order R-111-P (State of New Mexico 1988, 10), which is applicable within the potash leasing area that includes the WIPP site. The ~~purpose of the~~ continuous plug ~~is to~~ protect***s*** potash mining operations from possible hydrocarbon contamination. A continuous concrete plug is also used to approximate flow in boreholes ~~in which~~ ***with*** numerous concrete plugs ~~are found~~ throughout the salt section.

Table *6-27*~~6-25~~. Intrusion Borehole Properties for the BRAGFLO and CUTTINGS_S Models

Parameter (units)	Maximum	Minimum	Median or Constant[~~a~~ *1*]
Permeability of open hole (0 to 200 years) (square meters)	–	–	10^{-9}
Permeability of concrete plugs (0 to 200 years in Rustler and at surface) (square meters)[~~b~~ *2*]	***1×10^{-17}*** ~~–~~	***1×10^{-19}*** ~~–~~	10^{-18}
Permeability of borehole fill material (>200 years) (square meters)[~~b~~ *2*]	1×10^{-11}	1×10^{-14}	3.16×10^{-13}
Permeability of lower borehole fill material (>1,200 years) (square meters)[~~b~~ *2*]	1×10^{-12}	***5***~~1~~ × 10^{-17}~~15~~	***2.24***~~3.16~~ × 10^{-14}
Effective porosity (percent)	–	–	0.32
Pore compressibility (1/pascals)	–	–	0
Diameter (meters)	–	–	0.311
Threshold pressure, P_t (pascals)	–	–	0
Pore distribution parameter, λ (unitless)	–	–	0.94
Residual brine saturation, S_{br} (unitless)	–	–	0
Residual gas saturation, S_{gr} (unitless)	–	–	0

~~a~~ *1* Parameters with no maximum and minimum values are treated as constants in the ~~performance assessment~~***PA***.

~~b~~ *2* Borehole permeabilities are for the two-plug case. Continuous three-plug case is treated as undisturbed performance.

Examples of such plugging configurations currently used in the Delaware Basin are described in Appendix ***PA, Attachment*** MASS***,*** ~~(~~Section ~~MASS.~~16.3~~, and MASS Attachments 16-1 and 16-3)~~.

Because concrete within a continuous plug will be physically confined and will have very little brine flow through it, degradation will be minimal and limited to the upper and lower ends of the plug (see Appendix ***PA, Attachment*** MASS, Section ~~MASS.~~16.3.3~~ and MASS Attachment 16-3~~, Appendix C). For ***the CCA*** ~~performance assessment~~***PA*** the permeability of the continuous concrete plug ***was*** ~~is~~ 5×10^{-17} ***m^2 for all the plugging configurations. For this application, the DOE adopted EPA's 1997 PAVT range of 10^{-17} to 10^{-19} m^2.*** Because of the small cross-sectional area and low permeability of the potential pathway, long-term releases through a continuous concrete plug are not calculated explicitly for the ~~performance assessment~~***PA***, and are assumed to be zero.

6.4.7.2.2 The Two-Plug Configuration

In the two-plug configuration, two concrete plugs are assumed to have a significant effect on long-term flow in the borehole (Appendix ***PA, Attachment*** MASS, Section ~~MASS.~~16.3 and ***CCA Appendix*** MASS Attachment 16-3, Figure 2). The lower plug of interest is assumed to be located somewhere between the hypothetical Castile brine reservoir and underlying formations. A second plug is located within the lower portion of the Rustler, immediately above the Salado. Additional plugs that have little effect on long-term flow are also assumed to be present deeper in the hole and at the land surface.

In E1-type intrusions with two plugs, the brine reservoir and the repository are assumed to be in direct communication through an open cased hole immediately following drilling. The plugs are located in the borehole ***Column 26*** ~~Region 1A~~ of the BRAGFLO mesh in Figure ~~6-14~~ ***6-15*** in Rows 3***2***~~0~~ and 3***3***~~1~~ (the surface plug) and Row 2***5***~~3~~ (the ***Los Medaños*** ~~lower unnamed member~~). The plugs located below the brine reservoir are not modeled explicitly. Plugs are assigned initial ***sampled*** permeabilities of ***10^{-17} to 10^{-19}***~~5×10^{-17}~~ square meters ***pursuant to EPA's 1997 PAVT parameters.***~~, consistent with the expected properties of intact concrete (see Appendix MASS, Section MASS.16.3.2 and MASS Attachment 16-3, Appendix C.3.1.2 [C-4]).~~ The open segments of borehole between the plugs are assigned an initial permeability of 10^{-9} m^2. Steel casing above the Salado is assumed to begin to degrade within decades after abandonment and is assumed to have failed completely after 200 years. The concrete plugs above the Salado are also assumed to fail after 200 years, as a result of chemical degradation where they are in contact with brine. The plug below the Castile brine reservoir is in a less aggressive chemical environment, and its properties remain constant in ~~performance assessment~~***PA***.

After the upper plugs and casing have failed, the borehole is assumed to be filled by a silty, sand-like material containing degraded concrete, corrosion products, and material that sloughs into the hole from the walls. Thus, ~~beginning~~ 200 years after the time of intrusion, the entire borehole region in the BRAGFLO model, including the sections previously modeled as concrete plugs, is assigned a permeability corresponding to silty sand. This permeability is sampled from a log-uniform distribution from 10^{-11} square meters to 10^{-14} square meters.

One thousand years after the plug at the base of the Rustler has failed, ~~or 1,200 years after the time of intrusion,~~ permeability of the borehole region below the waste-disposal panel in the BRAGFLO model used for E1-type intrusions is decreased from its sampled value by one order of magnitude. For the remainder of the 10,000-year period, the borehole is modeled with its sampled permeability value above the repository and the adjusted value below. Conceptually, the decrease in permeability below the panel corresponds to compaction of the silty, sand-like material by partial creep closure of the ***borehole's*** lower portion~~ of the borehole~~. As discussed in Appendix ***PA, Attachment*** MASS***,*** ~~(~~Section ~~MASS.~~16~~ and MASS Attachment 16-3, Appendix D)~~, creep closure of boreholes ~~is~~ ***will*** not ~~expected to~~ be significant above the repository horizon but will be effective at greater depths because of the greater lithostatic stress. Nowhere in the borehole is creep closure assumed to close the hole completely in the regulatory time frame, but closure will be sufficient at depths below the repository to reduce the permeability of the material filling the hole.

6.4.7.2.3 The Three-Plug Configuration

In the three-plug configuration, three concrete plugs are assumed to ~~have an e~~***a***ffect ~~on~~ long-term flow in the borehole (Appendix ***PA, Attachment*** MASS, Section ~~MASS.~~16.3~~ and MASS Attachment 16-3, Figure 3~~). Two of the plugs are identical to those modeled in the two-plug configuration. The third plug is located within the Castile above the brine reservoir and below the waste-disposal panel. This plug is assumed to behave ~~in~~ the same ~~manner~~ as the lower plug in the two-plug configuration: that is, its properties remain unchanged in ~~performance assessment~~***PA***. Otherwise, all portions of the borehole in the three-plug configuration are assumed to have the same material properties as the corresponding regions in the two-plug configuration, with adjustments to borehole-fill permeability occurring 1,000 years after failure of the overlying plug (Appendix ***PA, Attachment*** MASS, Section ~~MASS.~~16.3~~ and MASS Attachment 16-3, Section 5.3~~).

Because the three-plug configuration isolates the repository from the brine reservoir for the time period during which the middle plug remains effective, and because the portion of the borehole above the middle plug will already be filled with silty, sand-like material before ~~failure of~~ the middle plug ~~occurs~~ ***fails***, the DOE ~~has~~ chose~~n~~ not to model this configuration explicitly in the BRAGFLO calculations. Boreholes in which the three-plug configuration is emplaced are assumed to result in long-term releases comparable to those calculated for E2 intrusions, regardless of whether they penetrate a Castile brine reservoir. Consequences of E1-type intrusions with the three-plug configuration are assumed for the purposes of CCDF construction to be identical to ~~the consequences of~~ ***those of*** E2 intrusions occurring at the same time.

6.4.8 Castile Brine Reservoir

As discussed by Section 2.2.1.2.2, high-pressure Castile brine was encountered in several WIPP area boreholes, including the WIPP-12 borehole within the controlled area and the ERDA-6 borehole northeast of the site. Consequently, the conceptual model for the Castile includes the possibility that brine reservoirs underlie the repository. The E1 and E1E2 scenarios include borehole penetration of both the repository and a brine reservoir in the Castile. The properties of the borehole are discussed in Section 6.4.7.

Unless a borehole penetrates both the repository and a brine reservoir in the Castile, the Castile is conceptually unimportant to PA because of its expected low permeability. Two regions are specified in the Castile horizon in the disposal system geometry: the Castile (Rows 1 and 2 in Figure 6-14) and a reservoir (Row 1, Columns 23 to 45 in Figure 6-15). The Castile region has an extremely low permeability, which prevents it from participating in fluid flow processes.

It is unknown whether a brine reservoir exists below the repository. As a result, the conceptual model for the brine reservoirs is somewhat different from those for known major properties of the natural barrier system, such as stratigraphy. The principal difference is that a reasonable treatment of the uncertainty of the existence of a brine reservoir requires assumptions about the spatial distribution of such reservoir and the probability of intersection (see Appendix MASS, Section MASS.18.1 and CCA MASS Attachment 18-6 for the development of the probability used in the CCA). The EPA required the DOE to use a range of probabilities for a borehole hitting a brine reservoir of 0.01 to 0.60 in the 1997 PAVT (EPA 1998, VII.B.4.d). The DOE added a parameter representing this range of subjective uncertainty for the CRA-2004 PA (Appendix PA, Section PA-3.5).

In addition to the stochastic uncertainty in the location and hence in the probability of intersecting reservoirs, there is also uncertainty in the properties of reservoirs. The manner in which brine reservoirs would behave if penetrated is treated as subjective uncertainty (see Section 6.2.2), and is incorporated in the BRAGFLO calculations of disposal system performance. The conceptual model for the behavior of such brine reservoir is discussed below.

Where they exist, Castile brine reservoirs in the northern Delaware Basin are believed to be fractured systems, with high-angle fractures spaced widely enough that a borehole can penetrate through a volume of rock containing a brine reservoir without intersecting any fractures and therefore not producing brine. They occur in the upper portion of the Castile (Popielak et al. 1983, G-2). Appreciable volumes of brine have been produced from several reservoirs in the Delaware Basin, but there is little direct information on the areal extent of the reservoirs or the existence of the interconnection between them. Data from WIPP-12 and ERDA-6 indicate that fractures have a variety of apertures and permeabilities, and they deplete at different rates. Brine occurrences in the Castile behave as reservoirs—that is, they are bounded systems. The properties specified for brine reservoirs are pressure, permeability, compressibility and porosity. Brine reservoir parameter values used in this PA are shown in Table 6-28.

Brine reservoir pressure in the PA is based on measured pressures in Castile and Salado anhydrites. These values are determined by analyzing brine pressures observed in Salado and Castile anhydrites, corrected for the difference in depth between the observed location and WIPP-12. The analysis is documented in CCA Appendix MASS (Section 18 and MASS Attachments 18-1 and 18-2) and Appendix PA (Attachment PAR, Parameter 27).

Table *6-28*~~6-26~~. Parameter Values Used for Brine Reservoirs in the BRAGFLO Calculations

Parameter (units)	Maximum	Minimum	Median or Constant~~a~~ *1*
Permeability (square meters)	1.58×10^{-10}	2.0×10^{-15}	1.58×10^{-12}
Effective porosity (percent)	***0.9208*** –	***0.1842*** –	***0.87*** –
Rock compressibility (1/pascals)~~b~~ *2*	10^{-10} ~~8~~	~~5~~2.0 × 10^{-11} ~~12~~	4 × 10^{-11} ~~10~~ ***(mode)***
Initial pressure (pascals)	1.70×10^{7}	1.11×10^{7}	1.27×10^{7}
Threshold pressure, P_t (pascals)~~c~~ *3*	4.59×10^{-6}	2.28×10^{-4}	4.6×10^{-5}
Pore distribution parameter, λ	–	–	0.70
Residual brine saturation, S_{br} (unitless)	–	–	0.20
Residual gas saturation, S_{gr} (unitless)	–	–	0.20
~~Maximum Capillary Pressure (pascals)~~	–	–	~~108~~
~~Brine Volume (cubic meters)~~	~~160,000~~	~~32,000~~	~~80,000d~~

~~a~~ *1* Parameters with no maximum and minimum values are treated as constants in the ~~performance assessment~~*PA*.

~~b~~ *2* Pore compressibility = rock compressibility/effective porosity.

~~c~~ *3* Threshold pressure (P_t) determined from the relationship: $PCT\_A \cdot k^{PCT\_EXP}$, where PCT_A and PCT_EXP are constants and k is the permeability.

d ~~There is equal probability of a brine volume less than 80,000 or greater than 80,000 cubic meters. However, 80,000 cubic meters is not a brine reservoir volume allowed in the model. See Appendix PAR.~~

The permeability of brine reservoirs is based on analyzing brine reservoirs tested by DOE in drillholes ERDA-6 and WIPP-12 (Popielak et al. 1983, Sections H-3.4.3 and H-3.4.4). Values used in the PA are shown in Table 6-28. The derivation of these values from the referenced study is documented in Appendix PA, Attachment PAR.

As discussed in Section 2.2.1.2.2, high-pressure Castile brine has been encountered in several WIPP-area boreholes, including the WIPP-12 borehole within the controlled area and the U.S. Energy Research and Development Administration (ERDA)-6 borehole northeast of the site.

The E1 and E1E2 scenarios include penetration by a borehole of the repository and a brine reservoir in the Castile. The properties of the borehole are discussed in Section 6.4.7.

For performance assessment, the Castile is conceptualized as unimportant because of its expected low permeability (based on similarities to the Salado), unless a borehole penetrates both the repository and a brine reservoir in the Castile. Two regions are specified in the Castile horizon in the disposal system geometry: the Castile (Region 29 in Figure 6-13)and a reservoir (Region 30 in Figure 6-13). The Castile region is assigned an extremely low permeability, which prevents it from participating in fluid flow processes, consistent with the concept that it is unimportant.

It is not known whether a brine reservoir actually exists below the repository. Because of this fact, the conceptual model for the brine reservoirs is somewhat different from those for known major properties of the natural barrier system, such as stratigraphy. The principal difference is that a reasonable treatment of the uncertainty of the occurrence of brine reservoirs requires that assumptions be made about their spatial distribution and probability of intersection (Appendix MASS, Section MASS.18.1 and MASS Attachment 18-6). foThese properties are treated as stochastic uncertainty in performance assessment modeling (that is, they are related to whether a brine reservoir exists and whether a brine reservoir intersection occurs; see Section 6.1.2). These assumptions are discussed in Section 6.4.12.

In addition to the stochastic uncertainty in the location and probability of intersecting reservoirs, there is also uncertainty in the properties of reservoirs if they are intersected (Appendix MASS, Section MASS.18 and MASS Attachments 18-2 and 18-3).This is treated as subjective uncertainty (that is, it is related to the question, f a brine reservoir is assumed to be penetrated, how does it behave?; see Section 6.1.2) and is incorporated in the BRAGFLO calculations of disposal system performance. The conceptual model for the behavior of the hypothetical brine reservoir is discussed here.

Where they exist, Castile brine reservoirs in the northern Delaware Basin are believed to be fractured systems, with high-angle fractures spaced widely enough that a borehole can penetrate through a volume of rock containing a brine reservoir without intersecting any fractures and therefore not produce brine. They occur in the upper portion of the Castile (Popielak et al. 1983, G-2). Appreciable volumes of brine have been produced from several reservoirs in the Delaware Basin, but there is little direct information on the areal extent of the reservoirs or the interconnection between them. The WIPP-12 data indicate that fractures in the network have a variety of apertures and permeabilities, and they deplete at different rates. Brine occurrences in the Castile behave as reservoirs—that is, they are bounded systems—rather than as aquifers such as groundwater in the Culebra and Magenta. The properties that need to be specified for brine reservoirs are pressure, permeability, compressibility, total brine volume, and porosity.

Brine reservoir pressure in this performance assessment is based on measured pressure in anhydrites in the Castile and Salado. The values used in this performance assessment are shown

~~in Table 6-26. These values are determined by analysis of pressures observed in brine produced from anhydrites in the Salado and Castile, corrected for the difference in depth between the observation location and WIPP-12. The analysis is documented in Appendix MASS (Section MASS.18 and MASS Attachments 18-1 and 18-2) and Appendix PAR (Parameter 27).The permeability of brine reservoirs is based on analysis of brine reservoirs tested by the DOE in drillholes ERDA-6 and WIPP-12 (Popielak et al. 1983, Sections H-3.4.3 and H-3.4.4). Values used in this performance assessment are shown in Table 6-26. The derivation of these values from the referenced study is documented in Appendix PAR (Parameter 28).~~

The bulk compressibility range is based on a reanalysis of WIPP-12 data that was requested by the EPA in their 1997 PAVT (EPA 1998). Beauheim (1997) provides a detailed description of this analysis and parameter range.

An effective porosity is defined for the reservoir portion of the Castile in the disposal system geometry (Row 1, Columns 23 to 45 in Figure 6-15). In the EPA's 1997 PAVT (EPA 1998), the EPA specified a range of brine volumes for the reservoir based on an EPA reanalysis of the amount of brine in the reservoir encountered by WIPP-12. The analysis concluded that PA should represent a total volume of brine in the brine reservoir that ranges between 3.40×10^6 and 1.70×10^7 m^3. Since the brine reservoir is represented by a region of constant volume, the effective porosity is used to provide the total brine volume in the reservoir rather than representing the actual value, and is not representative of the actual host rock's porosity. This treatment results in an effective porosity range between 0.1842 and 0.9208. The effective porosity is correlated to the values for the bulk compressibility (see Appendix PA, Section 4.2.1 for a detailed discussion of this relationship).

The CRA-2004 PA treatment of brine reservoir volume and porosity is consistent with the 1997 PAVT. In contrast, the CCA PA used a discrete distribution of brine volumes in the reservoir (see CCA Appendix MASS, Section MASS.18 and MASS Attachment 18-3).

The threshold pressure, pore distribution parameter, and residual saturations are parameters describing two-phase flow behavior and are required by BRAGFLO. Because saturations in the brine reservoir remain very near 1.0 in all preliminary and current PAs, the values of these parameters were not important to the model results. The parameter values used in the CRA-2004 PA are the same as those in the 1997 PAVT.

~~The compressibility of brine reservoirs is based on analysis (Appendix MASS and MASS Attachment 18-2) of data collected from the WIPP-12 brine reservoir (Popielak et al. 1983, G-33). Values used in this performance assessment are shown in Table 6-26. The derivation of these values is documented in Appendix PAR (Parameter 29). The range for Castile brine reservoir compressibility used in BRAGFLO is broad. This range was selected in an attempt to ensure that all possible values are encompassed Because the volume of brine that could be produced from a reservoir depends heavily upon the compressibility assumed, the brine volumes generated by the model reasonably bound those that would be produced from a Castile brine reservoir that could exist directly below the waste panels.~~

~~The brine reservoir volume is based on WIPP-12 observations and consideration of the effects of drilling 46.8 boreholes per square kilometer in the next 10,000 years in the vicinity of the site.~~

~~The interconnectivity, or extent, of a fractured reservoir is uncertain. Analysis of WIPP-12 data has led to estimates of the effective radius of reservoirs from several hundred meters to several kilometers (Appendix MASS, Section MASS.18.1 and MASS Attachment 18-3), where the effective radius is the area over which the fractured network of a single reservoir extends. Reservoirs interpreted as smaller have effective radii on the order of several hundred meters—in other words, dimensions somewhat smaller than the waste panel. This interpretation is generally supported by geophysical survey data (see Section 6.4.12.6 and Appendix MASS, Section MASS.18.1 and MASS Attachment 18-5). Reservoirs interpreted as large have effective radii much larger than the waste panel dimensions, or even the site dimensions. The DOE assumes that reservoirs that may exist under the waste panels have limited extent and interconnectivity with brine volumes consistent with the lower values estimated from the WIPP-12 encounter. The basis for this assumption is discussed in the following paragraphs.~~

~~Consistent with regulatory criteria in 40 CFR § 194.33(b)(3) regarding the rate of drilling used in performance assessment, the DOE assumes that 46.8deep boreholes may be drilled per square kilometer in the next 10,000 years. This drilling rate implies nearly 40-acre spacing of boreholes in the vicinity of the WIPP in 1,000 years, and nearly 5-acre spacing of boreholes at the end of 10,000 years. Even with limited probability of intersecting a brine reservoir (Section 6.4.12.6), there should be approximately one intersection per 480 acres in 1,000 years, and approximately one intersection per 48 acres in 10,000 years. Every time a reservoir of abnormally pressurized brine is penetrated, its pressure is partially depleted. Abnormally pressurized brine is defined as exhibiting pressure that exceeds the anticipated hydrostatic pressure for that depth. If reservoirs are well interconnected, they will be penetrated and partially depleted many times during 10,000 years until penetrating a reservoir no longer produces flow. If reservoirs are poorly interconnected, regions of pristine reservoirs could persist, although these would have lower producible brine volumes because of their limited extent.~~

~~There is an area in which potential brine reservoirs cannot be penetrated and depleted for some time—under the waste panels while passive institutional controls are effective. The passive institutional controls shield a region of the Castile from exploratory drilling. If brine reservoirs are well interconnected, the sheltered region could be depleted by the effects of multiple penetrations occurring in unprotected areas. If brine reservoirs are poorly interconnected, they could persevere under pristine conditions under the panels. The DOE considers that there are two reasonable conceptual models consistent with the drilling rate for the future condition of brine reservoirs in the WIPP region: (1) they are interconnected over large areas and penetrated and partially depleted many times; and (2) they are interconnected over small areas and not affected by the penetrations that occur outside but near the waste-area footprint. The DOE assumes that brine reservoirs potentially under the waste panels are poorly interconnected hydraulically (with extents similar to the lower estimates from WIPP-12), not much affected by penetrations occurring outside but near the waste-area footprint, and can persevere with pristine conditions until penetrated by a borehole drilled within the panel area. The DOE considers a pristine-condition, smaller reservoir to have potentially greater consequences than a depleted large reservoir. The distribution of brine volumes assumed in performance assessment for determining the consequence of first penetration of a brine reservoir ha five values: 32,000, 64,000, 96,000, 128,000, and 160,000 cubic meters (see Appendix MASS, Section MASS.18 and MASS Attachment 18-3). The smallest volume, 32,000 cubic meters, is the minimum volume from an analysis of WIPP-12 data (see Appendix MASS, MASS Attachment 18-3). Because this~~

~~WIPP-12 reservoir volume represents an estimated effective area of about one-third of the waste panel area and because a reservoir larger than the minimum WIPP-12 volume could reasonably exist under the waste panels, the DOE also considers larger reservoir volumes in performance assessment. In BRAGFLO, the brine volume is placed in a region of rock of constant dimensions. The porosity of the constant rock volume is set such that it contains pore volume equal to the reservoir brine volume. The porosity used for the largest reservoir is shown in Table 6-26. Porosities for smaller reservoirs are adjusted to yield the appropriate volume.The BRAGFLO calculations develop reference system behavior for possible future events. BRAGFLO calculations of the E1 scenario are executed for every vector. In the calculations, it is assumed that a brine reservoir exists beneath the waste panels, and it is assigned properties from LHS. Because there is a probability associated with the occurrence of a brine reservoir, there may be no penetration of a brine reservoir in a randomly determined sequence of future events. In this case, the BRAGFLO reference-condition results for a brine reservoir penetration are not used. The probability assigned to penetrating a brine reservoir is discussed in Section 6.4.12.6 and Appendix MASS (Section MASS.18 and MASS Attachment 18-6).~~

6.4.9 Climate Change

The present climate at the WIPP and the geologic record of past climate change in southeastern New Mexico are discussed in Section 2.5 and Appendix CLI ***of the CCA***. Although meaningful quantitative predictions of future climate for the next 10,000 years are not feasible ~~for the WIPP (or any location)~~, effects of reasonably possible climate changes on disposal system performance must be considered. For the WIPP, uncertainty about these effects is incorporated in the ~~performance assessment~~***PA*** by considering the effects of various possible future climates on groundwater flow and potential radionuclide transport in groundwater. Direct effects of climate change that do not involve groundwater flow do not affect the long-term performance of the WIPP because of its depth below the land surface. Examples of such direct effects are changes in wind patterns, thermal effects related to changes in surface temperature, and near-future impacts on surface facilities. Long-term effects of climate change on the near-surface portions of the shaft seal system (see Section 6.4.4) are not incorporated in the analysis because BRAGFLO modeling ~~conducted for this performance assessment~~ indicates that system performance is unaffected by the behavior of the shaft seal system***'s*** upper portion. Additional aspects of climate change screened out from the ~~performance assessment~~***PA***, including glaciation at the site and possible future anthropogenic changes, are discussed in Appendix ***PA, Attachment*** SCR (***FEPs N62 and H47 through H49*** ~~Sections SCR.1.6.2 and SCR.3.6.1~~).

The effects of postulated climate change on groundwater flow ~~have been~~ ***were*** evaluated outside of the ~~performance assessment~~***PA*** calculations using a regional three-dimensional groundwater basin model based on the ~~concept of~~ basin hydrology introduced in Section 2.2.1.1. For ~~the purposes of~~ the regional analysis, climate-related factors that might affect groundwater flow (such as precipitation, temperature, and evapotranspiration) are treated through a single model parameter, potential recharge, which controls the rate at which water is added to the model at the water table. As described in Appendix ***PA, Attachment*** MASS***,*** ~~(~~Section MASS***-***17***.0*** ~~and MASS Attachment 17-1)~~, changes in this parameter allow simulation of regional groundwater flow under a range of different future states in which the climate may be wetter, the water table may be higher, and groundwater velocity in all units may increase. These and other ~~simulated~~ simulations discussed in ***CCA*** Appendix MASS (Section MASS.15 and MASS Attachment 15-7) show that the regional, three-dimensional effects of climate change can be reasonably approximated in ~~performance assessment~~***PA*** ~~through~~ ***by*** direct***ly*** scaling ~~of~~ specific discharge in the two-dimensional, steady-state groundwater velocity field ~~for~~ ***of*** the Culebra. The velocity field is calculated using ~~SECOFL2D~~ ***MODFLOW-2000***, as described in Section 6.4.6.2 ~~and Appendix CODELINK (Section CODELINK.6.4)~~. Radionuclide transport in the Culebra is then calculated by SECOTP2D using the scaled velocity fields.

Scaling ~~of~~ the two-dimensional velocity field is done using the Climate Index (***Table 6-29***~~Table 6-27~~), ~~which is~~ a dimensionless factor by which the specific discharge in each grid block of the ***SECOTP2D*** ~~SECOFL2D~~ domain is multiplied. As summarized in Appendix ***PA, Attachment*** PAR (Parameter 48), the Climate Index is a sampled parameter in the ~~performance assessment~~***PA*** with a bimodal distribution ranging from 1.00 to 1.25 and from 1.50 to 2.25. A single value of the Climate Index is chosen in LHS for each sample element and held constant throughout the 10,000-year ***SECOTP2D*** ~~SECOFL2D~~ simulation. Each realization of disposal system performance thus represents a different approximation of future climate. Those

Table *6-29*~~6-27~~. Climate Change Properties for the *SECOTP2D* ~~SECOFL2D~~ Model

Parameter (units)	Maximum	Minimum	Median
Climate index (dimensionless)	2.25	1.00	1.17

realizations in which the sampled value is close to its maximum of 2.25 represent the most extreme changes in groundwater flow that may result from climatic change.

Sampled values close to the minimum of 1.00 represent climatic changes that have little effect on groundwater-flow velocities. Because all sampled values of the Climate Index are greater than 1.00, climate change as implemented in the ~~performance assessment~~***PA*** can only increase the rate of groundwater flow.

The distribution assigned to the Climate Index parameter is based on the results of three-dimensional basin modeling that considers future changes in the temporal pattern of potential recharge (see ***CCA*** Appendix MASS, Section MASS.17 and MASS Attachment 17-1, Section F). Potential recharge is defined ~~for the purposes of the regional modeling to be~~ ***as*** the maximum rate at which water can be added at the water table. Recharge itself is a model result and ranges from zero to the potential recharge. For those areas where the water table is at the ground surface and modeling indicates that water is discharging to the land surface through a seepage face, the potential recharge does not enter the model and has no effect on groundwater flow. In areas where the water table is below the land surface, potential recharge becomes actual recharge and tends to cause ~~elevation of~~ the water table to rise. If potential recharge is zero, the water table in an idealized basin will tend to fall until it is a horizontal plane with an elevation equal to the lowest topographic point in the basin. Sufficiently large values of potential recharge will cause the water table to rise to the land surface everywhere. Smaller, nonzero values result in solutions with water tables ~~that are~~ at the land surface at topographic low***s*** ~~points~~ (discharge areas) and at some distance below the land surface at topographic highs (recharge areas). Changes in potential recharge cause the elevation of the water table to rise or fall. In the three-dimensional modeling of the WIPP region, potential recharge was assumed to be spatially invariant across the regional model domain and ~~is~~ assumed to change through time in response to ~~in~~ climate changes.

Both steady-state and transient three-dimensional regional analyses ~~have been~~ ***were*** executed with values of potential recharge varied ~~such~~ ***so*** that the elevation of the water table ranged from approximately its present position to at or near the land surface. The latter condition provides an upper bound for regional groundwater-flow velocities during future wetter climates. For all simulations examining the effects of climate change, recharge is assumed to be greater at some time in the future than it is at present. Present recharge is assumed to be the same as its minimum value during the Holocene. The dominant effects on climate change during the next 10,000 years are assumed to be natural rather than anthropogenic. This assumption is consistent with regulatory guidance provided by the EPA indicating that ~~consideration of~~ ***considering*** the effects of climate change should be limited to natural processes (EPA 1996a, 61 FR 5227).

Because of uncertainty about recharge rates during future wet periods and the timing of these periods, transient analyses use two fundamentally different patterns for the change in potential recharge. The first pattern ~~for future potential recharge~~ used in the analysis corresponds to a continuation of the inferred climate patterns of the Holocene (see ~~Chapter 2,~~ Section 2.5.1 and ***CCA*** Appendix CLI, Section 3), with wetter peaks occurring 500, 2,000, 4,000, 6,000, 8,000, and 10,000 years in the future. Potential recharge is assumed to increase and decrease linearly during the wet periods 500 years before and after the peaks, and the wet periods are each separated by 1,000 years of a drier climate, like that of the present. Several different values were examined for the maximum potential recharge imposed at the wet peaks; ~~with~~ the largest value ***was*** chosen to provide a steady-state solution with the water at, or close to, the land surface throughout the model domain. As discussed in Appendix MASS (***CCA*** Section MASS.17 and MASS Attachment 17-1, Section F), a continuation of the Holocene climatic variability is considered likely during the next 10,000 years, and ~~this function~~ is assigned a relatively high probability of occurrence (0.75). This recharge function and its probability of occurrence are reflected in the lower portion of the bimodal distribution assigned to the Climate Index parameter.

The second recharge pattern ~~considered in the analysis~~ assumes that potential recharge will increase from its present value to a specified larger value 500 years in the future, and that potential recharge will then remain constant throughout the rest of the 10,000-year simulation. As with the Holocene pattern, several different values were examined, ~~with~~ the largest ~~being sufficient to~~ result***ing*** in a steady-state solution with the water table at, or close to, the land surface throughout the model domain. Conceptually, this pattern corresponds to a future in which the climate either becomes continuously wetter or the frequency of wetter periods becomes ~~sufficiently~~ large ***enough*** that the hydrologic response is indistinguishable from that of a continuously wetter climate. Step-increase recharge functions were used to simulate the effects of major disruptions of the Holocene climate, analogous to those that might occur during the next 10,000 years in a transition from the present warm interglacial climate to the early stages of a future glacial climate. As discussed in ***CCA*** Appendix MASS (Section MASS.17), such disruptions to the Holocene climate are considered unlikely, and the step function is assigned a relatively low probability of occurrence (0.25). This recharge pattern and its probability of occurrence are represented by the upper portion of the bimodal distribution assigned to the Climate Index parameter.

As reported in ***CCA*** Appendix MASS (Section MASS.17 and MASS Attachment 17-1, Section E), 17 transient and 54 steady-state, regional, three-dimensional, groundwater-flow simulations were run to examine effects of climate change. Simulations considered both potential recharge functions with varying peak recharge rates and different sets of assumptions about regional rock properties. Total specific discharge into and out of the Culebra within a model region was calculated for each simulation approximately corresponding to the controlled area. Values for the Climate Index parameter were determined by comparing the total lateral specific discharge calculated for each simulation. The largest observed increase in flow for those simulations using realistic values of rock properties was a factor of 2.1. Although some simulations produced a slight reduction in flow, Climate Index parameter values less than 1.0 are not considered in the ~~performance assessment~~***PA***. Changes in flow direction in the Culebra were also noted in some three-dimensional simulations, with a shift in flow toward the west corresponding to a regional increase in the elevation of the water table. These potential changes in flow direction are not incorporated in the two-dimensional flow and transport modeling to simplify the computational process. This treatment is conservative with respect to radionuclide transport because the most rapid transport possible under any climate conditions will be through the most conductive portion of the Culebra south and east of the repository. Any shift of the flow ~~direction~~ away from this high conductivity zone would result in slower transport through less permeable rock. Restricting the effects of climate change to a uniform linear scaling of specific discharge in the ***SECOTP2D*** ~~SECOFL2D~~ model is, therefore, a conservative assumption.

6.4.10 Initial and Boundary Conditions for Disposal System Modeling

The solution of many mathematical models used in ~~performance assessment~~***PA*** requires specification of a starting point, called initial conditions, and specification of how the region modeled (that is, volume) interacts with the regions not modeled (~~called~~ boundary conditions). Initial values are required for all of the parameters appearing in a computer code. In practice, however, the term ***"***initial conditions***"*** refers to the values assigned to the primary variables used to describe the system, examples of which may be pressure, composition, and saturation. The term ***"***boundary condition" refers to the specification of primary variables that control the interaction of the modeled region with the regions excluded from the model. In many studies, applied boundary conditions are static in time, although computer codes that implement time-dependent boundary conditions are not uncommon. A common practice in modeling groundwater flow is to place ~~boundaries of the~~ modeled system ***boundaries*** somewhat distant from the region in which model results are of interest. This ~~is done to~~ help***s*** ensure that uncertainty in the natural boundaries of the system does not unduly influence model results in the region of interest. The DOE adopts this practice in its application of BRAGFLO and ~~SECOFL2D~~ ***MODFLOW-2000*** to the WIPP.

The following sections describe the initial and boundary conditions specified for the major codes used in this ~~performance assessment~~***PA***. Initial values of parameters not discussed in the following sections are set equal to the values assigned from the ~~performance assessment~~***PA*** database or LHS sampling ~~that are~~ discussed elsewhere in Section 6.4.