EEG-13

HEALTH & ENVIRONMENT department

Analysis of the Potential Formation of a Breccia Chimney Beneath the WIPP Repository

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State of New Mexico

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Environmental Evaluation Group Reports

EEG-1 Goad, Donna. A Compilation of Site Selection Criteria, Considerations and Concerns Appearing in the Literature on the Deep Disposal of Radioactive Wastes, June 1979.

EEG-2 Review Comments on Geological Characterization Report, Waste Isolation Pilot Plant (WIPP) Site, Southeastern New Mexico SAND 78-1596, Volumes I and II, December 1978.

EEG-3 Neill, Robert H., et al, eds. Radiological Health Review of the Draft Environmental Impact Statement (DOE/EIS-0026-D) Waste Isolation Pilot Plant, U. S. Department of Energy, August 1979.

EEG-4 Little, Marshall S. Review Comments on the Report of the Steering Committee on Waste Acceptance Criteria for the Waste Isolation Pilot Plant, February 1980.

EEG-5 Channell, James K. Calculated Radiation Doses From Deposition of Material Released in Hypothetical Transportation Accidents Involving WIPP-Related Radioactive Wastes, November 1980.

EEG-6 Geotechnical Considerations for Radiological Hazard Assessment of WIPP. A Report of a Meeting Held on January 17-18, 1980, April 1980.

EEG-7 Chaturvedi, Lokesh WIPP Site and Vicinity Geological Field Trip. A Report of a Field Trip to the Proposed Waste Isolation Pilot Plant Project in Southeastern New Mexico, June 16 to 18, 1980, November 1980.

EEG-8 Wofsy, Carla. The Significance of Certain Rustler Aquifer Parameters for Predicting Long-Term Radiation Doses From WIPP, September 1980.

EEG-9 Spiegler, Peter. An Approach to Calculating Upper Bounds on Maximum Individual Doses From the Use of Contaminated Well Water Following a WIPP Repository Breach, September 1981.

EEG-10 Radiological Health Review of the Final Environmental Impact Statement (DOE/EIS-0026) Waste Isolation Pilot Plant, U. S. Department of Energy, January 1981.

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FOREWORD

The purpose of the Environmental Evaluation Group (EEG) is to conduct an independent technical evaluation of the potential radiation exposure to people from the proposed Federal radioactive Waste Isolation Pilot Plant (WIPP) near Carlsbad, in order to protect the public health and safety and ensure that there is minimal environmental degradation. The EEG is part of the Environmental Improvement Division, a component of the New Mexico Health and Environment Department -- the agency charged with the primary responsibility for protecting the health of the citizens of New Mexico.

The Group is neither a proponent nor an opponent of WIPP.

Analyses are conducted of available data concerning the proposed site, the design of the repository, its planned operation, and its long-term stability. These analyses include assessments of reports issued by the U.S. Department of Energy (DOE) and its contractors, other Federal agencies and organizations, as they relate to the potential health, safety and environmental impacts from WIPP.

The project is funded entirely by the U.S. Department of Energy through Contract DE-AC04-79AL10752 with the New Mexico Health and Environment Department.

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SUMMARY

This report evaluates the potential formation of a Breccia pipe beginning at the Bell Canyon aquifer beneath the WIPP repository and the resulting release of radioactivity to the surface. Rock mechanics considerations indicate that the formation of a Breccia pipe by collapse of a cavern is not reasonable. Even if rock mechanics is ignored, the overlying strata act as a barrier and would prevent the release of radioactivity to the biosphere. Gradual formation of a Breccia pipe is so slow that the plutonium-239 in the waste (one of the most important long-lived components) would decay during formation. If Bell Lake and San Simon Sinks are the surface manifestation of a regional deep dissolution wedge, such a wedge is too far removed to represent pipe forming activity near the WIPP site.

The formation of a breccia pipe under the WIPP repository is highly unlikely. If it did occur, the concentration of plutonium-239 in brine reaching the surface would be less than the maximum permissible concentration in water specified in the Code of Federal Regulation Title 10, part 20.

I. Introduction

Two features in the vicinity of the WIPP site, Hills A and C, have been proven through coring to be breccia chimneys*(Ref. 1). Both chimneys seem to have resulted from the collapse of caverns beneath the Salado formation, and both chimneys are located on the Capitan Reef which may have played an important role in their formation.

Even though the WIPP site is not located over the Capitan Reef formation, it has been suggested that deep-seated dissolution beneath the WIPP repository using water from the Delaware Mountain Group (DMG) aquifer could create a cavern which upon collapse would lead to the formation of a breccia pipe and bring about the release of radioactive waste to the biosphere. Thus, L. W. Gelhar has proposed the following release model (Ref. 2).

> "Collapse of an underlying breccia pipe chamber and displacement of the brine associated with dissolution and collapse to the surface, resulting in the surface release of brine and radioactive materials and direct exposure in the biosphere."

In the Final Environmental Impact Statement (FEIS) (Ref. 3) and in the Safety Analysis Report (SAR) (Ref. 4), the DOE maintained that the breccia pipe release model is bounded by scenario 1, which postulates a 9-inch diameter vertical connection between the lower Bell Canyon aquifer and the upper Rustler aquifer, and which allows a flow of up to 600 cubic feet of water per day through the repository. The DOE contention is plausible but it has been pointed out that scenario 1 only brings radioactivity to the Rustler aquifer from where it slowly flows to Malaga Bend. A scenario that brings radioactivity directly to the surface at the WIPP site may be more representative of a breccia chamber collapse.

In this report, it is assumed that a breccia pipe can be formed by deep-seated dissolution of salt beginning at the Bell Canyon aquifer under the repository.

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*The phrases Breccia pipe and Breccia chimney are used interchangeably.

It is not intended to imply that breccia pipes are necessarily formed by this process. Data soon to be published by the USGS suggest that breccia pipes at Hills A and C resulted from the collapse of caverns located in the limestone of the Capitan Reef.

II. Formation of Breccia Pipe in General

There are two interesting studies which deal with the formation of breccia chimneys (Refs. 5, 6). The study of Stanton (5) proposes two mechanisms which will be referred to as "Process" (a) and "Process" (b) and which are illustrated in Figure 1.

Process (a):
As a result of some trigger mechanism, a communication channel is established between the lower aquifer and the salt formation (see area of deep-seated dissolution in Figure 1). The dissolving of evaporites causes the formation of a cavern which collapses upon reaching a critical size. The breccia chimney results from a series of such collapse events or from a single catastrophic collapse.

Process (b):
Again a communication channel is established between the lower aquifer and the salt formation. However, solution of evaporite and flowage of salt occur simultaneously. Because of salt flowage, no cavern is formed but brecciation occurs in the strata overlying the salt formation. Simultaneously, small scale precipitation occurs in the area of deep-seated dissolution. The breccia chimney is formed slowly rather than by a series of catastrophic collapse events.

Stanton also suggests that Process (a) is more likely to occur in shallow regions while Process (b) is more likely to occur in deeper regions. The two processes can be viewed as complementing each other and it is assumed in this report that Process (a) will occur if the creep rate of salt is slower than the rate of removal of salt by groundwater (see Figure 2) while Process (b), occurs if the reverse is true. However, the two processes would produce different types of brecciated rocks.

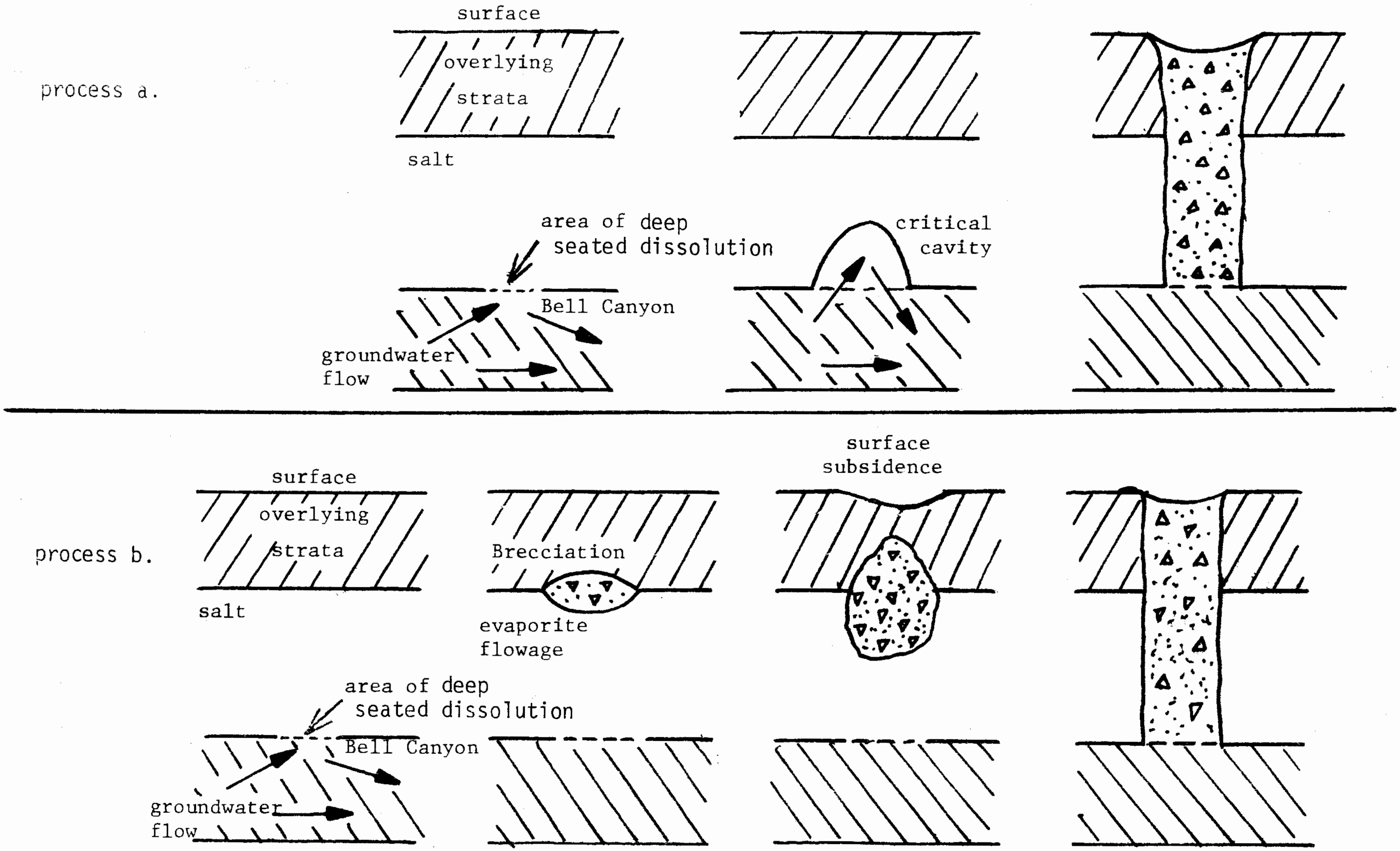

Figure 1. Sequential events in the formation of Breccia pipe.

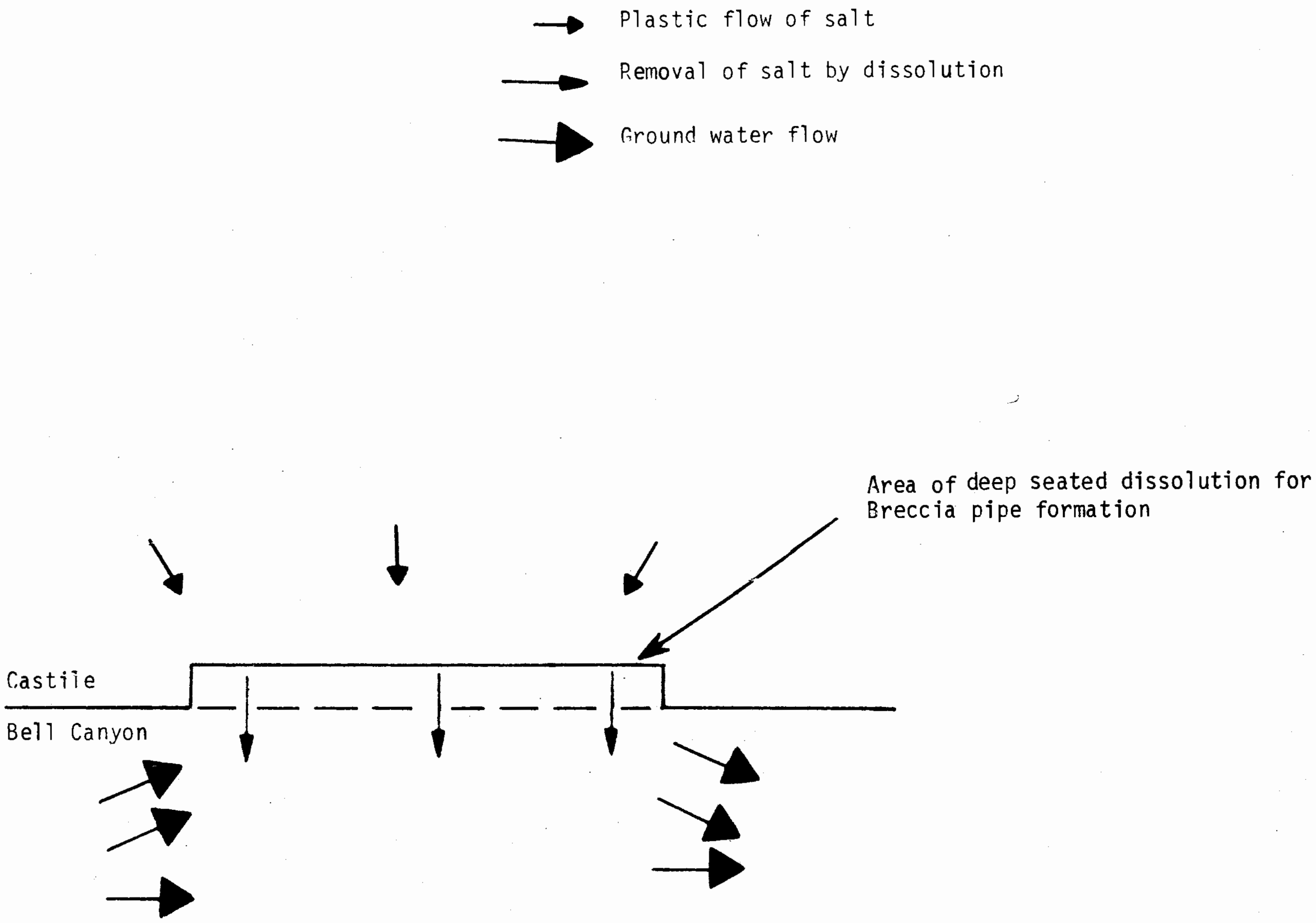

Figure 2. Movement of salt and water in the formation of a cavity.

III. Potential for Formation of a Breccia Pipe at the WIPP repository site

For Process (a) to occur, it must be hypothesized that a large cavity will form at the top of the DMG formation 4000 ft below the surface. Placing the cavern at the Salado-Castile interface is unrealistic and a detailed analysis is presented in Appendix A.

However, geologists are in agreement that Hill C resulted from a catastrophic collapse event (Refs. 7, 8). It is not possible to predict the size of the largest cavern that can be formed at a depth of 4000 feet. The volume of the cavern that formed Hill C is estimated to be 570,000 m^3 based on a breccia chimney diameter of 245 m (Bachman, ref. 8, p 63) and a vertical distance of fall of brecciated rock of 12 m. (Bachman states that of Hill A a large block from the Rustler formation fell 7.7 to 15 m, Ref 8, p 66)*. It is shown in Appendix B, that for the current hydrological conditions in the Bell Canyon aquifer, a cavern cannot be formed. The creep of overlying salt is much greater than the removal of salt by the postulated deep-seated dissolution.

Process (b), which requires continuous dissolution and removal of salt between the top of the DMG and the Salado, can occur since at present the creep of overlying salt is greater than the removal of salt by groundwater. However, a salt column 580 m tall (380 m of Castile and 200 m from top of Castile to repository level) must be dissolved before the repository will collapse to the top of DMG. At a vertical dissolution rate of 4.5×10^{-4} m/yr (see Appendix B), a 580 m salt column will be removed in 1.3 million years.

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*Data soon to be published suggest that a drop of 12 m. in Hill A is too small (private communication from R. Snyder USGS). The core data of WIPP-31 suggests that in Hill A the Rustler dropped 55 to 88 m. The Fletcher anhydrite, which separates the Salado formation from the Capitan Reef, appears to have dropped 76 m., indicating that the caverns were in the limestone of the Capitan Reef. Core data from WIPP-16 indicates that in Hill C the Rustler formation may have dropped 113 m. Thus, the caverns that formed Hills A and C had volumes of millions of cubic meters. These new numbers do not alter the conclusions in this report for the formation of a larger cavern is less credible.

IV. Release Models

As emphasized in the previous section, there is no justification for assuming that Process (a) can occur below the WIPP site. However, it may be interesting to consider the consequences, if one does assume that Process (a) occurs and that a 570,000 m^3 cavern can be formed under the WIPP repository. The scenario is then as follows: As the roof of the cavity collapses, overlying salt and rock drop down while saturated brine moves up. The collapse process may be relatively fast, at most a few days, and the volume of the cavern subsequently leads to increased porosity of the breccia chimney. The chimney is permeable for several years and its pore space is filled with brine that occupied the cavern or came from the DMG aquifer. Water can flow up or down and slowly leach radioactivity from the repository area affected by the chimney. Upon emerging from the Salado, upward flowing contaminated brine must move through 800 feet of brecciated rock from the Rustler and Dewey Lake red bed formations. The flow is slow and radionuclides are adsorbed on the rock. Finally, contaminated brine reaches the surface and fills the sink at the top of the Breccia chimney. From there radioactivity enters the biosphere.

Process (b) allows for the following release model. The repository level slowly sinks to the depth of the Bell Canyon. Radioactivity is then leached out by brine of the Bell Canyon aquifer, transported about 14 miles to the Capitan Reef, and pumped to the surface through wells.

V. Radiological Consequences

If we ignore the creep closure of the cavity, it is estimated in Appendix C that, in the collapse of a 570,000 m^3 cavern below the repository, 23,000 Ci of Pu-239 become available for leaching into the brine. The collapse of such a large cavern would create vertical cracks; however, if it is assumed that the volume of the cavern is absorbed by an increase in porosity in the chimney resulting in the 1200 m (4000 ft) of overlying strata, then the average increase in porosity would be 0.01 or 1 percentage point. The contaminated brine must travel through 500 feet of Dewey Lake Redbed formation which contains large amounts of clay. Because of the sorption on clay, only a very small amount of the Plutonium can reach the biosphere. As described in Appendix C, the radiological impact is not significant.

The release model for Process (b) has no radiological impact and the analysis is shown in Appendix D. In addition to the time it takes the repository to sink to the top of Bell Canyon, the travel time from the WIPP site to the edge of the Capitan reef formation is 640,000 years for the water alone, 8,300,000 years for the uranium, and essentially infinite for plutonium. All the U-233, Pu-239, and Pu-240 would decay in the period necessary for formation and travel to the Capitan.

VI. Bell Lake and San Simon Sink

These two depressions, which exhibit structural collapse features, are often mentioned when discussing present-day pipe forming activity in the area surrounding the WIPP site. They could be due to a deep-seated dissolution wedge located at a depth corresponding to the horizon of the repository and moving into the Delaware basin from the east. The following analysis assumes deep seated dissolution and uses the dimensions and age of the structures as given in Reference 9. It should not be construed as an elaborate discussion of these two features. Additional geological characterization of these two depressions may alter the numbers substantially.

Bell Lake Sink is a depression about 3240 m (2 miles) in diameter and located about 24 km (15 miles) southeast of the WIPP site. The volume inside the boundaries of collapse is estimated to be $1.7\text{x}10^7$ m^3 ($6.0\text{x}10^8$ ft^3). Bell Lake Sink Began forming in the Wisconsin period and is probably 20,000 yr old. If the sink is due to deep-seated dissolution, it is the the result of an average dissolution rate of

$$\frac{1.7 \times 10^7}{20{,}000 \times 365} = 2.3 \text{ m}^3/\text{day}$$

Now consider a salt column 24 km (15 miles) long, 3.24 km (2 miles) wide, and 400 m (1300 ft) thick (See cross-hatched area connecting Bell Lake Sink and WIPP site in Fig. 3). At an average dissolution rate of 2.3 m^3/day (82 ft^3/day), it would take the dissolving wedge 37 million years to dissolve all the salt between Bell Lake Sink and the repository.

San Simon Sink is a collapse structure 32 km (20 miles) from the WIPP site in the southeastern part of the San Simon Swale. The sink has a diameter of approximately 1620 m (1 mile) and the core from the WIPP 15 well indicates a 46 m (150 ft) collapse. The collapse volume is estimated to be 9.4 x 10^7 m^3 (3.3 x 10^9 ft^3). San Simon Sink also began forming in the Wisconsin Period and is perhaps 20,000 years old. The average dissolution rate is thus 13 m^3/day (450 ft^3/day). Again Consider a salt column 32 km (20 miles) long, 1620 m (1 mile) wide, and 400 m (1300 ft) thick (see cross-hatched area connecting San Simon Sink and the WIPP site in Fig. 3), at an average dissolution rate of 13 m^3/day (450 ft^3/day) it would take the dissolution wedge 4.1 million years to dissolve all the salt between San Simon Sink and the horizon of the repository.

Because of the long time periods needed for the dissolution wedge to reach the repository, this dissolution process is not a threat to the repository.

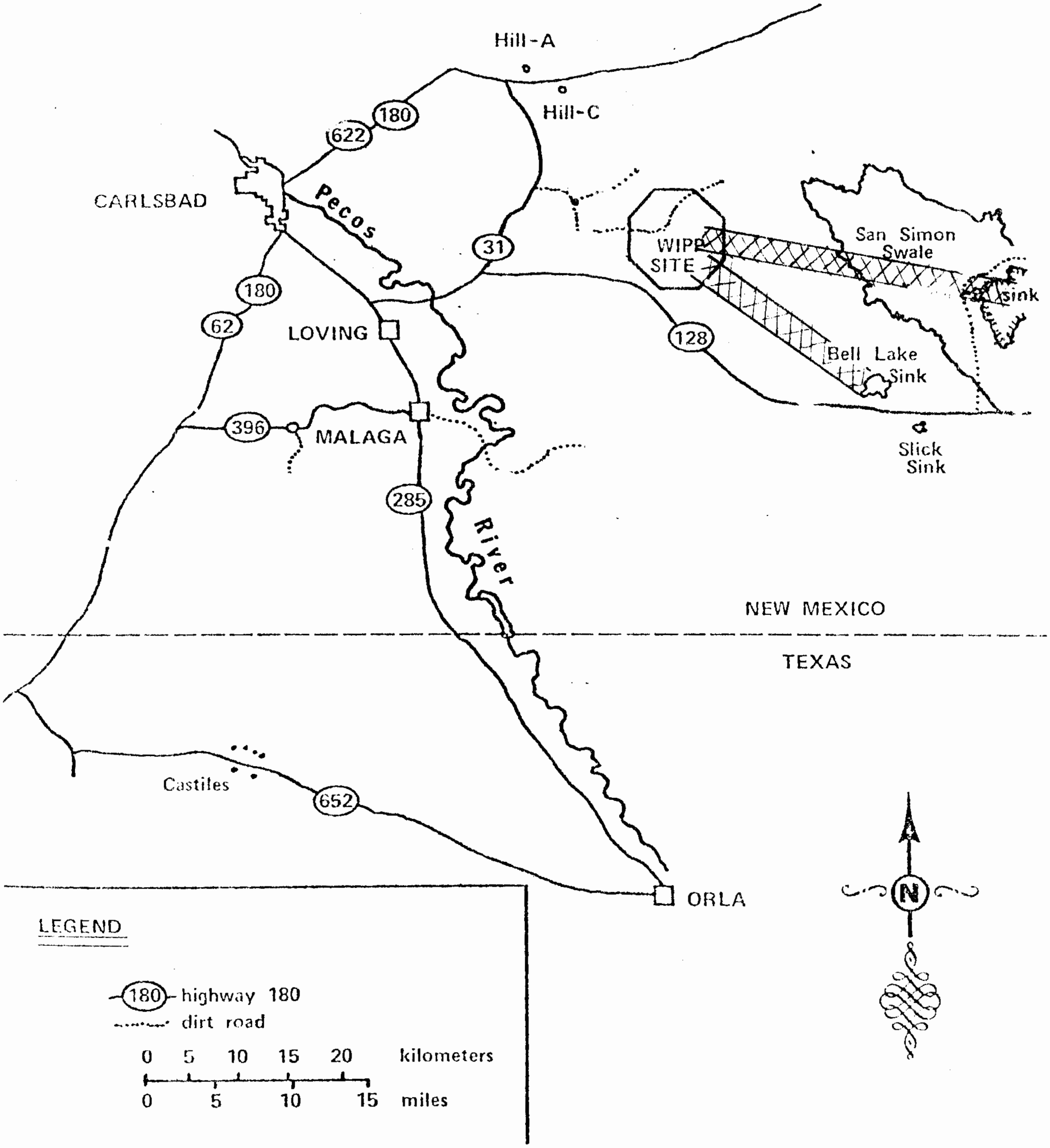

Figure 3. Bell Lake Sink, San Simon Sink, and the WIPP Site.

Appendix A

Arguments Against a Cavern Forming at the Salado-Castile Interface:

R. Y. Anderson (10) has proposed "brine density flow", essentially natural convective flow upward through fractures as a flow cycle capable of carving out large chambers in the Salado formation. According to this hypothesis, unsaturated water from the DMG aquifer rises to the Salado formation through fractures of the Castile formation from a hydrostatic head. Dissolution of salt at the top increases the water density which causes the downward flow of brine.

The onset of steady convection in a fluid at rest in a vertical cylindrical channel along with maintenance of a constant temperature gradient is discussed in the work of Landau and Lifschitz (Ref. 11)*. The discussion is applicable to long pipes when the end effects can be neglected and it can be applied to "brine density flow" by replacing the density gradient due to temperature by a density gradient due to dissolved salt.

The onset of steady convection is characterized by the Rayleigh number

$$Ra = \frac{\Delta\rho}{l\rho} \frac{R^4 g}{D\nu} \qquad \text{A-1}$$

where

$\frac{\Delta\rho}{l\rho}$ = density gradient over length of pipe, cm^{-1}

R = radius of pipe, cm

g = acceleration due to gravity, 980 cm/sec^2

D = Diffusivity constant for salt in water $1.3x10^{-5}$ cm^2

ν = kinematic viscosity for saline, 0.012 cm^2/sec

In the limiting case of no salt deposition along the walls, steady state convection will be initiated if $Ra>67.4$. In the opposite limiting case of walls with complete deposition of salt, steady state convection will begin if $Ra>215.8$.

*A forthcoming report by D'Appolonia entitled "Delaware Mountain Group (DMG) Hydrology-Salt Removal Potential" has a very elaborate discussion of brine density flow.

The thickness of the Castile formation at the repository site is about 380 m (1250 ft) and the density of DMG water is about 1.1 gm/cm^3 (Total Dissolved solids concentration of 150,000 mg/ℓ). The density of saturated brine is about 1.2 gm/cm^3. The density gradient over the thickness of the Castile formation is thus

$$\frac{\Delta\rho}{l\rho} = \frac{0.1}{3.8\text{x}10^4\text{x}1.2} = 2.2\text{x}10^{-6}\ \text{cm}^{-1}$$

For a cylindrical fracture the length of the Castile formation, steady state convection will set in if its diameter is greater than 0.53 cm for no salt deposition along the wall, and 0.71 cm for complete salt deposition along the wall.

Following the onset of free convection, the velocity distribution of water is such that water flows up in one half of the cylinder and flows down in the other half (Ref. 11). The density gradient produces a driving headwhich is calculated as follows:

$$\Delta H_d = (l\Delta S)/2 \qquad \text{A-2}$$

where

ΔH_d = driving head due to density difference, cm

ΔS = difference in specific gravity of in flowing and out-flowing water, 0.1

l = length of connection, 3.8 x 10^4 cm.

For non-circular pipes, the lost head due to laminar flow is given by (Ref. 12)

$$\Delta H_f = \frac{f}{4}\frac{L}{R_h}\frac{V^2}{2g}$$

$$f = \frac{64}{Re} \qquad \text{A-3}$$

$$Re = \frac{V(4R_h)}{\nu}$$

where

ΔH_f = Lost head due to laminar flow, cm

L = length of flow path, 7.6×10^4 cm

R_h = hydraulic radius, cross-section area to wetted perimeter. For a half-circle of radius R, $\pi R/[2(\pi+2)]$; 0.08 and 0.11 cm.

V = Velocity of flow. cm/sec

g = acceleration due to gravity, 980 cm/sec^2

f = friction factor

Re = Reynolds number

ν = kinematic viscosity, 0.012 cm^2/sec

Equating the driving and lost head, one obtains velocities of 6.4 and 11.6 cm/sec for 0.5 and 0.7 cm cylindrical channel respectively. The Reynolds numbers are 170 and 420 respectively, which indicates laminar flow. The annual flow rates are 20 and 70 m^3 respectively. If each m^3 of water can transport 0.1 m^3 of salt (Bell Canyon water is half saturated) then the times to remove 570,000 m^3 of salt through one fracture are 286,000 and 81,000 yr respectively.

To form a cavern at the Castile-Salado interface, unsaturated brine would have to travel long distances through salt layers and remain unsaturated. (The Castile formation consists of thick layers of salt and anhydrite.) It is thus necessary to look at the following problem: Given a long cylindrical pipe in a large block of salt with fresh water entering at one end; determine the length of the pipe over which the salinity is raised to a fraction, "x", of saturated salinity.

In analogy to heat transfer (Refs. 13, 14, 15) the average Nusselt number for mass transfer is given by

$$Nu_d = \frac{h_m d}{DC} = 3.66 + \frac{(0.0668)\,[(d/l) ReSc]}{1 + (0.04)\,[(d/l)\,ReSc]^{2/3}} \qquad \text{A-4}$$

where

Nu_d = Average mass transfer Nusselt number for a tube of diameter d

h_m = Average convective mass transfer coefficient, gm salt dissolved/m^2-sec

d = diameter of pipe, cm

D = Diffusivity constant for salt in water, 1.3×10^{-5} cm^2/sec

C = Concentration of salt in saturated brine, gm salt/cm^3

l = length of cylindrical pipe over which salinity is raised to a fraction x of saturated salinity.

Re = Reynolds number, Vd/ν

Sc = Schmidt number ν/D

V = Velocity of water, cm/sec

ν = kinematic viscosity for saline, 0.012 cm^2/sec

x = fraction of saturation

The second term in equation A-4 is a correction term for lack of fully developed flow in the entry length. It will be neglected to simplify the calculations; hence

$$\frac{h_m d}{DC} = 3.66 \qquad \text{A-5}$$

A salt balance on the fluid yields

$$x C \frac{\pi}{4} d^2 V = h_m \pi l d \qquad \text{A-6}$$

Introducing A-5 into A-6 and solving for ℓ one obtains

$$l = \frac{x d^2 V}{14.6D}$$

For 0.5 and 0.7 cm diameter cylindrical channel and assuming 100% saturation of brine, one obtains ℓ=84 and 300 m respectively which is less than the thickness of the Castile formation.

In view of the calculations of this appendix, it is not possible to place the cavern at the top of the Castile formation.

Appendix B

Possibility of the Formation of a Cavern at the DMG-Castile Interface:

Large cavities deep in salt formations are unstable because of the viscoplastic properties of rock salt. The phenomenon is very important in the design and operation of gas storage cavities in salt formations (Refs. 16, 17, 18, 19) where it has been studied in great detail. Although the closure of such cavities is usually studied with powerful rock mechanics computer codes (Refs. 16, 17), empirical formulas have also been advanced (Ref. 18). In this report, the cavity will be treated as a cylinder to avoid the use of a computer code and because theoretical formulas verified by experiments are available (Ref. 20). For a cylindrical drift, the radial convergence rate at the inner surface is given by

$$u_a = \frac{\sqrt{3}}{2} A\ a \left[\frac{p\sqrt{3}}{n} \right]^n \qquad \text{B-1}$$

when the secondary creep strain rate is described by

$$\varepsilon_c = A\ \sigma^n \qquad \text{B-2}$$

where

A = a constant

σ = homogeneous stress within material under consideration

n = an exponent, 4.9 for the bedded salt of the Delaware basin (Ref. 21)

a = radius of drift

p = external pressure

If the radial convergence rate is u_a for a drift of radius a, at a depth d, it can then be obtained by equation B-1 for another drift by scaling as follows

$$\frac{u_{a1}}{u_{a2}} = \frac{a1}{a2} \left[\frac{p1}{p2}\right]^n \qquad \text{B-3}$$

In performing numerical calculations, the following assumptions are made:

1. A cylindrical cavity of diameter 4.2 m at a depth of 958 m (2922 ft) has drift closure rates of 1.5 cm/yr. This assumption is based on the measured drift closure rates at the Esterhasy potash mine in Saskatchewan, Canada (Ref. 21). The drift is 2.35 m high and 6 m wide (average 4.2 m). The horizontal drift closure rate is about 1 cm/yr at the walls and the roof closure rate is about 2 cm/yr (average 1.5 cm/yr).

2. The 570,000 m^3 cavern is approximated by a cylindical drift 245 m long and 27.2m in radius.

3. The effective external pressure on the cavern is equal to the lithostatic pressure (1220 m ore 4,000 ft of soil or salt with a density of 2.2) minus the hydrostatic pressure of water in the Bell Canyon (1160 m or 3800 ft. of water). The effective external pressure at the Bell Canyon is equivalent to 1220 -1160/2.2 = 693 m of salt or soil with a density of 2.2.

4. The exponent n for salt of the Delaware basin is assumed to be 4.9.

The drift closure rate for the 570,000 m^3 cavern is estimated to be

$$1.5 \, \frac{27.2}{2.1} \left[\frac{693}{958}\right]^{4.9} = 4 \text{ cm/yr}$$

The convergence rate of volume in percent is

$$\frac{2\pi a l u_a}{\pi a^2 l} \times 100 = 0.29 \text{ percent/year}$$

The model used to estimate the rate of salt removal is illustrated in Figure 3. The following mass balance equation is used:

$$\left\{\begin{array}{c}\text{Salt dissolved at}\\ \text{cross section}\\ \text{area A}\end{array}\right\} = \left\{\begin{array}{c}\text{concentration}\\ \text{of salt in}\\ \text{saturated brine}\end{array} - \begin{array}{c}\text{concentration}\\ \text{of salt in}\\ \text{incoming water}\end{array}\right\} \times$$

$$\left\{\begin{array}{c}\text{height}\\ \text{of Bell}\\ \text{Canyon}\end{array}\right\} \times \left\{\begin{array}{c}\text{width}\\ \text{of zone}\\ \text{A}\end{array}\right\} \times \left\{\begin{array}{c}\text{velocity}\\ \text{of inflowing}\\ \text{water}\end{array}\right\}$$

$$\rho hA = (C_s - C_i) \times H \times D \times V$$

$$h = \frac{(C_s - C_i)\ H \times D \times V}{\rho A}$$

The following numbers describe the present hydrological conditions in the Bell Canyon below the WIPP repository (Ref. 22).

$C_s - C_i = 150$ gm NaCl/l

$H = 1000$ feet $= 300$ meter

$D = 245$ m

$V = 3.8 \times 10^{-3}$ m/yr, see Appendix D

$\rho = 2000$ gm/l

$A = 4.7 \times 10^4 m^2$

$h = 4.5 \times 10^{-4}$ m/yr

The rate of increase of the volume of the cavity in percent is

$$\frac{h'A}{hA} \times 100 = 3.75 \times 10^{-3} \text{ percent/year.}$$

A comparison of the convergence rate of volume due to salt creep and the rate of increase of volume of the cavity due to salt removal is not readily possible since the geometries in the two calculations are different. However, the convergence rate of volume is almost 100 times greater than the increase rate of

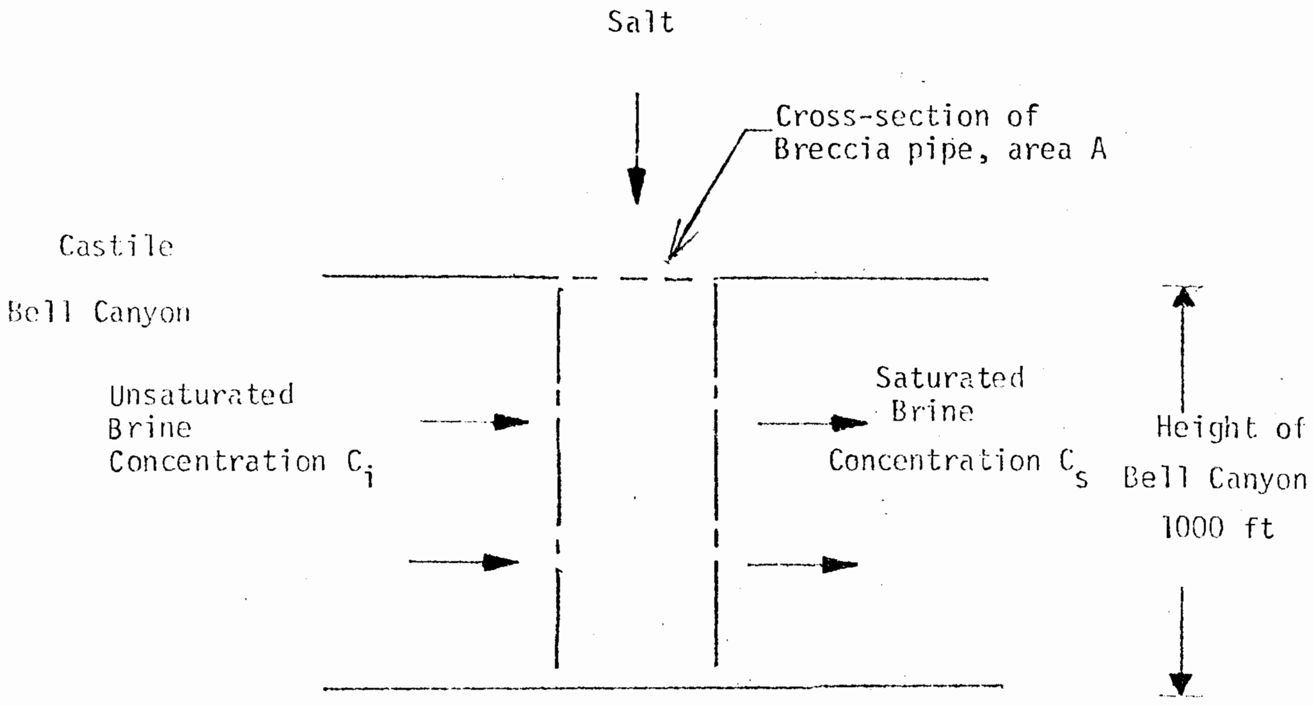

Figure 4. Mass balance of Dissolution process in the formation of a Breccia Pipe

volume due to salt removal. Because of this difference in magnitude, the formation of a large cavern at the Bell Canyon-Castile interface is not believed to be possible under present hydrologic and geologic conditions.

By means of equation B-3, it can be shown that the closure rate equals the salt removal rate if the diameter of the cylinder is about 0.6 m in diameter. The permissible cavern is thus 300 m^3 (cylinder 0.6 m in diameter and 245 m long).

To be acceptable for estimating the closure of caverns beneath the WIPP site, equation B-3 must also predict the possibility of forming a 570,000 m^3 cavern under Hill C. At that location, the Salado-Capitan reef interface is 550 m (1800 ft) below the surface and 520 m (1700 ft) above sea level. The head in the Capitan Reef aquifer is about 980 m of water (3200 ft). The effective external pressure on the cavern would be equivalent to

$$550 - \frac{(980 - 520)}{2.2} = 340 \text{ m}$$

of salt or soil with a density of 2.2. The drift closure rate for the 570,000m^3 cavern is then estimated to be

$$1.5 \times \left[\frac{27.2}{2.1}\right] \times \left[\frac{340}{958}\right]^{4.9} = 0.12 \text{ cm/year}$$

The convergence rate of volume in percent is .9 x 10^{-2} per cent/yr.

The hydraulic conductivity of the Capitan Aquifer is at least 50 times that of the Bell Canyon (Ref. 3) and the salt content is much less. The Capitan Aquifer is twice as thick as the Bell Canyon aquifer. The hydraulic gradients are comparable. The salt removal rate at the Capitan Reef - Salado interface could thus be 200 times greater than at the Bell Canyon-Castile interface or 4.5 x 10^{-2} m/yr. The rate of increase of volume in percent is 0.70 percent/yr or almost 100 times greater than the convergence rate of volume due to creep of salt.

Bachman discussed the origin of the breccia pipes on the Reef during Gatuna time (Ref. 8). He believes that the present hydrologic conditions are not suitable for the formation of new breccia pipes over the Capitan Reef.

Appendix C

Radiological Consequences From a Cavern Collapse Beneath the WIPP Site

At the end of emplacement, WIPP will have 425,000 Ci of Pu-239. At a vertical salt removal rate of 4.5 x 10^{-4} m/yr (see Appendix B), a cavity 245 m in diameter and 12 m high could be formed in 27,000 years. The amount of Pu-239 at the time of the roof collapse will be 200,000 Ci.

The WIPP repository will cover an area of 100 acres (405,000 m^2) while the cross-sectional area of the chimney is 47,100 m^2; the amount of radioactivity available for release is

$$200{,}000 \times \frac{47{,}100}{405{,}000} = 23{,}200 \text{ Ci}$$

It will be assumed that following the collapse, all the volume of the cavern is transferred as equivalent porosity to the brecciated chimney rubble. The chimney is permeable for several years and its pore space is filled with brine that can flow upward. all the radioactivity in the affected area is leached and an equilibrium is established between the plutonium in the brine and the plutonium adsorbed on the rock of the Dewey Red Lake Bed formation which is 150 m thick (500 ft) and which has large amounts of clay.

To a rough approximation,

$$C_s = K_d C_l \qquad \text{C-1}$$

C_s = concentration per unit mass of a given nuclide sorbed on solid mineral phase, Ci/gm

C_l = Concentration per unit volume in the liquid phase, Ci/ml

K_d = distribution coefficient, ml/gm

Assuming that equilibrium is established as the contaminated brine moves through Dewey Lake Red Bed formation, one obtains for the distribution of plutonium between soil and liquid

$$m_s C_s + V_l C_l = 23{,}200 \text{ curies} \qquad \text{C-2}$$

where

m_s = mass of solid available for sorption, gm

V_l = Volume of liquid, ml

Combining C-1 and C-2 one obtains

$$C_l = \frac{23{,}200}{m_s K_d + V_l} \qquad \text{C-3}$$

For clay of the Delaware basin, K_d for Pu-239 varies between 40,000 and 180,000 ml/gm (Ref. 23). Finally, assume that only 1 percent of the brecciated Dewey Red Lake Bed formation (thickness 150 meters) becomes available for sorption. The input data to C-3 consists of

$$m_s = \frac{\pi}{4} (245)^2 \times \frac{150}{100} \times 2.2 \times 10^6 = 1.6 \times 10^{11} \text{ gm}$$

V_l = 570,000 m^3 = 5.7×10^{11} ml

K_d = 40,000 ml/gm

and the output is

C_l = 3.7 pCi/ml

which is less than 5 pCi/ml [the MPC_w value for Pu-239, (Ref. 24)]

Appendix D

Radionuclide Transport in the DMG Aquifer

The average interstitial fluid speed in an aquifer is given by

$$V = \frac{K}{\theta}\frac{dh}{dl}$$

where

K = Average hydraulic conductivity, m/sec

θ = Average porosity

dh/dl = hydraulic gradient

Because of the adsorption and desorption of nuclides as they pass through the rock, the movement of nuclide is slower than the velocity of water. The nuclide velocity is given by the water velocity divided by the retardation factor B

$$V_n = V/B$$

$$B = 1 + \frac{\rho}{\theta} K_d$$

where

V_n = nuclide velocity, m/yr

V = water velocity, m/yr

ρ = formation density gm/ml

K_d = distribution coefficient, ml/gm

The time of travel between the repository and the Capitan Formation is then calculated from

$$T = \frac{Bd}{V}$$

where

d = distance from WIPP site to Capitan Reef Formation, m.

From available hydrologic data for the Bell Canyon aquifers (Refs. 2, 3, 22)

$K = 0.016$ ft/day $= 5.6 \times 10^{-8}$ m/sec

$\theta = 0.16$

$dh/dl = 2.16 \times 10^{-3}$

the water velocity V is thus 2.3 x 10^{-2} m/yr and since the distance between the center of the repository and the Capitan Reef formation is 10 miles (17,000 meters), the water travel time alone is 740,000 years.

The distribution coefficients, K_d, are assumed to be 1 ml/gm for all uranium isotopes and 2.4 x 10^3 ml/gm for all plutonium isotopes. The retardation factors, B, for these isotopes are thus 13 for all uranium isotopes and 3 x 10^4 for all plutonium isotopes. The travel time is thus 8,300,000 years for all uranium isotopes and essentially infinite for all Pu isotope, since the half lives of U-233, Pu-239 and Pu-240 are 240,000 years, 24,400 years and 6,500 years respectively. As pointed out in section III, the formation of the breccia chimney is 1.3 million years, thus all radionuclides would decay either during the formation of the chimney or in the transit to the Capitan Reef formation.

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