Numerical Modeling Tools for the Prediction of Solution Migration Applicable to Mining Sites

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Abstract

Mining has always had an important influence on cultures and traditions of communities around the globe and throughout history. Today, because mining legislation places heavy emphasis on environmental protection, there is great interest in having a comprehensive understanding of ancient mining and mining sites. Multi-disciplinary approaches (i.e., Pb isotopes as tracers) are being used to explore the distribution of metals in natural environments. Another successful approach is to model solution migration numerically. A proven method to simulate solution migration in natural rock salt has been applied to project through time for 10,000 years the system performance and solution concentrations surrounding a proposed nuclear waste repository. This capability is readily adaptable to simulate solution migration around mining.

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1.0 Introduction

Mining legislation places increased emphasis on environmental protection. In many areas around the globe, detailed environmental impact statements must be performed that ensure that the environment and population are protected. This protection must be ensured well beyond the active life of the mine itself. Multi-disciplinary approaches are being used to explore the distribution of metals in natural environments. For example, in order to evaluate the extent and behavior of migrating contaminants, tracers are being injected and monitored around ancient and abandoned mining sites. Another approach is through the use of numerical models (computer codes) which incorporate fundamental laws of physics to predict the migration of metals in solution far into the future. These models can be validated by comparisons to the injected tracer studies around mine sites.

Underground repositories (natural or engineered excavations) in which hazardous or radioactive materials are to be stored for extended periods of time make excellent surrogates for studying the behavior of solution migration around mines. The Waste Isolation Pilot Plant (WIPP) is the first deep geological repository in the world to be certified for the disposal of transuranic waste[1,2,3,4,8]. During the past ten years, detailed numerical models have been developed for predicting solution migration and release of contaminants through the surrounding host rock. These same models can be readily applied to the evaluation of solution migration around mines.

In this paper, a brief description of the WIPP is first presented. This is followed by a conceptualization of what occurs at the WIPP in the underground. Next, four of the numerical models that have been used to evaluate solution and contaminant migration are described. Using the WIPP site as a surrogate for a mine, these models are applied and results are presented. Two scenarios are modeled: one in which the repository remains undisturbed and one in which the repository is breached by an exploratory well.

2.0 Description of the Waste Isolation Pilot Plant Repository[1,2]

The WIPP is a mined geologic repository designed to demonstrate the safe management, storage, and disposal of mixed transuranic (TRU) radioactive wastes. The WIPP is located in southeastern New Mexico near Carlsbad, New Mexico, USA (Figure 1), at a depth of 655 m below the ground surface in bedded evaporites of the Permian-age Salado formation.

The WIPP repository (Figure 2) is constructed on one level in the 600 m-thick bedded salt of the Salado formation, which dips slightly to the south. The salt is interspersed with thin horizontal interbeds of anhydrite. The repository level consists of an experimental region at the north end, the operations region in the center for waste handling, and the disposal region at the south end. Ultimately, eight panels of seven rooms each will be mined. The total facility covers an area approximately 775 m × 1585 m, and the tunnels are initially 4.0 m in height. The total excavated volume of the facility is 583,400 m^3 and it is designed to hold 176,000 m^3 of waste. Before the repository is closed permanently, each panel will be backfilled with MgO and sealed. Waste will be placed in the drifts between panels; the access ways will be sealed off from the shafts, and the four shafts (waste handling, salt handling, air intake and air exhaust shafts) will be sealed.

3.0 The WIPP Compliance Standards

Before disposing of radioactive waste at the WIPP, the United States Department of Energy (DOE) must comply with the United States Environmental Protection Agency (EPA) [9]. Releases are sometimes reported in terms of an "EPA Unit,"[2] defined as a isotopic-specific unit of measure that is equal to the number of curies represented by the release limit of the EPA requirements.[9] A release occurs when a regulated contaminant passes the Land Withdrawal Boundary[9] (LWB) and enters the "accessible environment[9]" 2.4 kms. from the repository wall.

4.0 The Numerical Models

Because compliance with the regulation requires quantitative prediction of the migration of contaminants from the repository over a 10,000-year period, we have had the opportunity to develop and use a suite of mechanistic numerical models. These numerical models are based on fundamental laws of physics and rely on field and experimental measurements made in and around the excavation, such as hydrologic and transport properties of the host rock. This same type of data and the ability of the numerical models to use this information are required if predictions of solution migration and transport of minerals around mines are to be made.

4.1 BRAGFLO (BRine And Gas Flow) MODEL[10]

The first step toward the prediction of the migration of dissolved species in a liquid solution is the determination of the fluid flow in and around the mine or repository. Because of gas generation in the repository, a model capable of predicting the simultaneous flow of gas and brine is required in the application to the WIPP. BRAGFLO is a numerical model that simulates the simultaneous flow of immiscible fluids through porous media in one, two, or three dimensions. It has been extensively verified and has undergone rigorous quality assurance testing and documentation.

4.2 NUTS (NUclide Transport Simulator) Model[11]

The next code in the suite is a transport code, NUTS, developed for predicting the migration of radionuclides and other contaminants around the WIPP repository. The results of the fluid flow simulations from BRAGFLO are used as input into NUTS along with the transport characteristics of the solute and formation. The principle physical and chemical processes applied to the WIPP NUTS application are advective transport in a porous media, radioactive decay and ingrowth (creation of new species do to the decay process), dissolution in the brine phase, and precipitation of solute out of solution.

4.3 SECOFL2D (Sandia national lab/ECOdynamics Flow, 2D) Model[12]

Not all situations require a fully coupled multi-phase flow model such as BRAGFLO. Many situations associated with mines can be treated by considering saturated flow only. SECOFL2D has been developed for simulating flow in a fully saturated host rock. In the WIPP, it is used to predict the migration of contaminant solution through an overlying water bearing dolomite unit (the Culebra Member of the

Rustler formation) that could connect to the underlying repository via an inadvertent human intrusion borehole drilled sometime in the future. SECOFL2D predicts the direction, velocity, and travel times of the plume through the Culebra.

4.4 SECOTP2D (Sandia national lab/ECOdynamics TransPort, 2D) Model[13]

Once the flow field in the Culebra is established, the migration of solute in the contaminant plume can be predicted. The transport code, SECOTP2D, models a number of processes that affect the migration of the solute in the Culebra: 1) advection in the natural flow of the groundwater, 2) adsorption of contaminants onto portions of the host rock, and 3) dispersion and diffusion of a plume as it migrates.

5.0 Simulation of Solution and Contaminant Migration

Because regulations require that a performance assessment of the repository consider both undisturbed and human intrusion scenarios for 10,000 years[9], simulations of the repository are described and results are presented for both an undisturbed scenario and a representative human intrusion scenario (borehole) for the 10,000 years. For the undisturbed simulation, the numerical models BRAGFLO and NUTS are required for prediction of solution migration, while the full suite of models (BRAGFLO, NUTS, SECOFL2D, and SECOTP2D) is utilized in the human intrusion scenario.

Rather than one deterministic simulation of solution migration around the underground repository, sets of simulations were performed. By performing many simulations using differing, but probable, parameter values, we translate the uncertainty in input to a range of consequences (predictions of solution migration), any of which is possible. Many of the results are displayed as time histories of entire sets of simulations (100 simulations in the case of the WIPP evaluation). These time histories show the range of possible consequences given the uncertainties present in the various measured input parameters.

5.1 Undisturbed Scenario Description[2,8]

Figure 3 is a schematic of the undisturbed scenario. Identified are two likely pathways to the accessible environment. The first is upward through the sealed shaft system directly to the surface or into the overlying water-bearing unit, the Culebra, and laterally to the accessible environment. The second is through the DRZ surrounding the waste disposal regions, into the more permeable anhydrite interbeds, and laterally to the LWB.

Figures 4a, 4b, and 4c depict a progression of what may occur conceptually (and what we observed from our simulations) in the repository during undisturbed conditions. In Figure 4a, the waste drums are shown in the excavation shortly after emplacement. The stress field produces a DRZ around the excavation, and rock bolts are emplaced through the ceiling and into the anhydrite layers to support the roof during the waste emplacement period (5 years per panel). The surrounding host rock is salt (halite) of low porosity, and the voids are saturated with brine. The anhydrite interbeds are similarly of low porosity, but more transmissive, and saturated with brine. There is no natural flow in the Salado formation.

The repository is sealed, and brine flows toward the excavation from the far field because of the low-pressure associated with the excavation, Figure 4b. This brine primarily flows through the anhydrite interbeds, through the DRZ, and into the excavation. The halite has a strong tendency to creep under the lithostatic load and over time encapsulates the waste. In the waste disposal region, waste consolidation continues until back-stresses imposed by the compressed waste resist further closure or until fluid pressures become sufficiently high. Within the first few hundred years, the excavation collapses to 1 to 2 m in height from its original 4-m height. The porosity is reduced from 84 % to 40 %. The waste drums are crushed exposing their contents. Brine flows through the excavation in contact with the metal drums and their contents. The radionuclides and other soluble contaminants dissolve in the brine according to their solubility properties. Additionally, the brine contacts the metal and biodegradable constituents of the waste resulting in the generation of gases and consumption of brine.

In Figure 4c, continued gas generation occurs resulting in pressure that may approach lithostatic, 14.7 MPa. Gas is forced out of the repository, either driving brine outward or retarding its rate of inflow. As the pressure approaches lithostatic, the host rock responds. There is some reversal of the creep consolidation, and fractures begin to develop. This relieves pressure and provides for pathways for fluid flow and potential release to the accessible environment. In the long term, the pressure in the repository is capped naturally by the lithostatic load.

5.2 Undisturbed Scenario Results[5,6]

5.2.1 BRAGFLO Results

Gas Generation

The predicted rate and amount of gas generation varies significantly (Figure 5). Among the 100 realizations, the volume of gas generated varies over more than an order of magnitude, from 1.5×10^6 m^3 to 2.8×10^7 m^3 of hydrogen, at standard conditions. This variation is associated with uncertainty over the 10,000-year regulatory period in repository chemistry, in the rate of corrosion and biodegradation, in what constituents will biodegrade, and in uncertainty in the rate at which brine contacts the waste.

The corrodible metal is never completely consumed in 10,000 years. In realizations where corrosion ceases, it is a lack of brine in the waste that causes corrosion to stop. In contrast, biodegradation (if it occurs), completely consumes the inventory of cellulosics.

Halite Creep

Halite creep causes the pore volume of the repository to decrease over time. As shown in Figure 6, the porosity of the waste drops from its initial porosity of 84.8 % during the first few hundred years as the repository creeps shut. The porosity reaches a minimum between 7 % and 22 % of the initial excavated volume (somewhat larger if based on the collapsed volume), depending on the rate at which the pressure in the repository increases.

Repository Pressure

Pressures in the repository increase from their initial value of 1 atmosphere (Figure 7). The pressure increases are driven by a number of competing processes: 1) brine inflow and pressure equilibration with the surrounding host rock, 2) gas generation, 3) creep consolidation of the surrounding halite, and 4) pressure relief through developing fractures.

Fluid Flow

Cumulative brine flows out of the repository are shown in Figure 8. This brine cannot migrate significant distances in halite because of the low permeability of halite. To get to the LWB[6,9], brine from the repository must first flow through the DRZ into one of the permeable anhydrite interbeds or up the sealed shafts. Not all of the brine leaving the repository enters the anhydrite interbeds. Additional analysis indicates a maximum of 3700 m^3 enters the interbeds over 10,000 years.

The cumulative flows across the LWB in the marker beds are small. Brine volumes crossing the LWB during the 10,000-year regulatory period range up to 216 m^3. The NUTS transport calculations indicate that there are no significant concentrations of solute contaminants in this brine.

5.2.2 NUTS Results[6]

The flow results from BRAGFLO indicate that in some cases brine flows across the subsurface LWB into the accessible environment. The results from the transport calculations indicate cumulative releases of all radionuclides in this brine are on the order of 10^{-17} to 10^{-10} EPA units (3.4×10^{-15} to 3.4×10^{-8} curies). None of these releases is considered significant.

NUTS transport calculations also indicate that none of the brine predicted by BRAGFLO that flows up the shafts to the Culebra is contaminated.

5.3 Typical Human Intrusion Scenario Description[2,8]

Figure 9 is a schematic of a human intrusion scenario. This particular human intrusion event is one in which a future driller (1000 years after the closure of the repository) inadvertently drills through the repository and also hits a pressurized brine pocket underneath the repository. In this situation (see also Figure 4d), brine from the brine pocket flows upward into the repository and contacts waste. Some of the contaminants in the waste dissolve in the brine according to their solubility characteristics. This solution then exits the repository through the borehole and continues upward where it enters the Culebra. The contaminated solution mixes with the water in the Culebra and flows with it toward the LWB. The migration of the contaminant plume over 10,000 years must be predicted, as must the concentrations of the various solute contaminants.

BRAGFLO is used to determine the velocity and flow field of brine and gas in the repository and host rock. Particularly important in this scenario, it determines the rate of flow through the repository, the fraction in contact with the waste, and the rate of flow exiting the repository up the intrusion borehole and entering the Culebra. NUTS uses the flow fields determined by BRAGFLO along with the transport properties of the contaminants to predict, as a function of time and space, the concentrations of solute in the brine entering the Culebra. The important output from NUTS in this scenario is rate of injection of solute into the Culebra. SECOFL2D calculates the flow of the groundwater through the Culebra. SECOTP2D uses this flow along with the time dependent injection of solute from NUTS and the transport characteristics of the solutes in the Culebra to predict the migration of the solution plume. This plume is characterized for each contaminant of interest as a spatially and temporally varying concentration field.

5.3.1 BRAGFLO Results[5]

As in the undisturbed scenario, repository behavior is characterized by interactions among creep closure, fluid flow, and gas generation. Creep closure of excavated regions begins immediately because of excavated induced loading. In the waste disposal region, waste consolidation will continue until back-stresses imposed by the compressed waste resist further closure or until fluid pressures become sufficiently high. In the undisturbed scenario, the extent of gas generation in many cases is controlled by the availability of brine, the principal source of which is the halite and anhydrite layers surrounding the repository. In the human intrusion scenario, the borehole provides a pathway for additional sources of brine from two locations: 1) flow down the borehole from the Rustler and Dewey Lake formations overlying the Salado, and 2) flow up the borehole from the pressurized brine reservoir in the Castile formation underlying the Salado. Predicted gas generation results indicate that the increased availability of brine increases the amount of gas generated by corrosion by approximately 40 %.

A large portion of the generated gas escapes up through the borehole to the surface. This venting is reflected in lower pressure in the repository after the intrusion takes place. This pressure reduction causes increased creep consolidation under the lithostatic load compared to the undisturbed scenario.

Fluid Flow

Immediately following the borehole intrusion, as much as 44,000 m^3 of brine flows up from the Castile brine reservoir into the repository over 10,000 years (Figure 10). Comparable quantities flow downward from the Dewey Lake formation into the repository (Figure 11). Up to 21,500 m^3 of brine flows up the borehole out of the repository over 10,000 years (Figure 12).

Brine flow up the shafts is small compared to the flow up the borehole, ranging from 0 m^3 to 48 m^3. Transport simulations show this brine to be uncontaminant brine resident in the shaft sealing system.

In addition to the shaft and borehole pathways, brine can migrate to the land withdrawal boundary through one of the more permeable anhydrite interbeds. In the intrusion scenario, less than 300 m^3 of brine flow out of the DRZ and into the marker beds over 10,000 years. This occurs because the borehole is the path of least resistance to the accessible environment. Less than 1.5 m^3 of brine flows out all anhydrite layers and across the LWB 2.4 km away from the repository over 10,000 years. Transport calculations show that none of this brine is contaminated.

5.3.2 NUTS Results[6]

The BRAGFLO predictions of brine flow indicate a number of representations of the human intrusion scenario result in brine flow to the Culebra. The NUTS transport simulations, using these flow fields, indicate this brine has been contaminated by the waste. The integrated discharge up the borehole to the Culebra for these representations is shown in Figure 13 for four of the most persistent radionuclides. The contaminants must still be carried 2.4 km laterally through the Culebra to reach the accessible environment.

The transport calculations verify no releases by any other pathways in this intrusion scenario.

5.3.3 SECOFL2D Results[7]

The NUTS simulations show a number of situations that result in release of dissolved contaminant to the Culebra dolomite. SECOFL2D and SECOTP2D are used to evaluate the extent to which these solutes migrate through the Culebra.

Results of the Culebra flow calculations from SECOFL2D are best visualized in terms of travel times and flow paths. The 100 computed flow paths (Figure 14) show the direction of flow of a particle from the point of its release into the Culebra (i. e., the intrusion borehole) to the accessible environment. The variations are associated with uncertainty in the hydrologic characteristics of the formation from field measurements. In general the computed groundwater flow results show the direction of flow in the Culebra to be from north to south or southeast. The travel time provides a quantitative measure of the magnitude of the velocity field along the flow paths. In Figure 15, travel times are presented for the 100 simulations of the flow field in the Culebra. Travel time as short as 10,000 years and as long as 250,000 years are predicted.

5.3.4 SECOTP2D Results[7]

Once the flow field through the Culebra is quantified, the migration of specific solutes in this flow field can be predicted. This is done using the numerical model SECOTP2D. Linearity in the transport process allows for uncoupling of the transport from the injected source term. Transport calculations are performed using a unit injection of radionuclide contaminant. The concentration of contaminants and potential release are then appropriately scaled to reflect the actual inject of contaminant into the Culebra from the previous NUTS simulations. In only two of the 100 solution transport simulations performed were non-zero releases to the LWB predicted. The 100 simulations account for uncertainty in both transport characteristics of the solutes and the hydrologic characteristics of the Culebra. In Figure 16, a time progression of the contaminant plume for ^{234}U is presented for the largest release realization using the unit injection source. The plume reaches the accessible environment after 6,000 years. In Figure 17, the contaminant plume at 10,000 years for ^{239}Pu is depicted. Because of high absorption characteristics of plutonium, it does not travel nearly as far (a few 10s of meters) as ^{234}U. When scaled appropriately the releases to the LWB are orders of magnitude below the EPA regulations.[8]

6.0 Conclusion

The licensing of WIPP demonstrates the success in applying mathematical models to simulate solution migration and the evolution of this underground repository over an extended period of time.

7.0 FIGURES

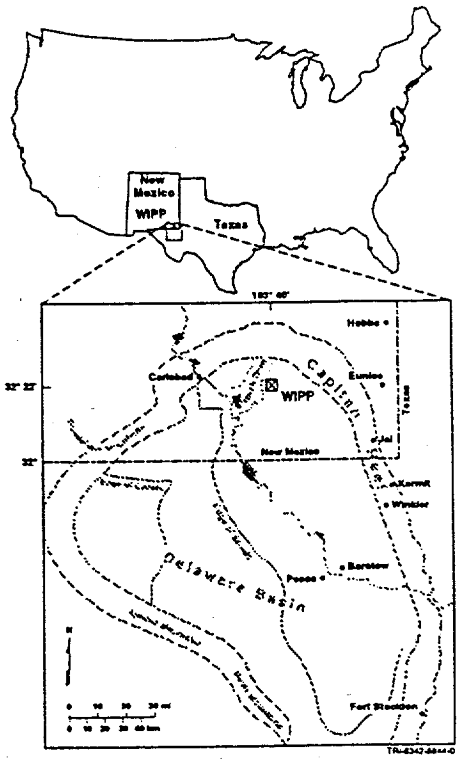

Figure 1: WIPP site location in Southeastern New Mexico, USA..

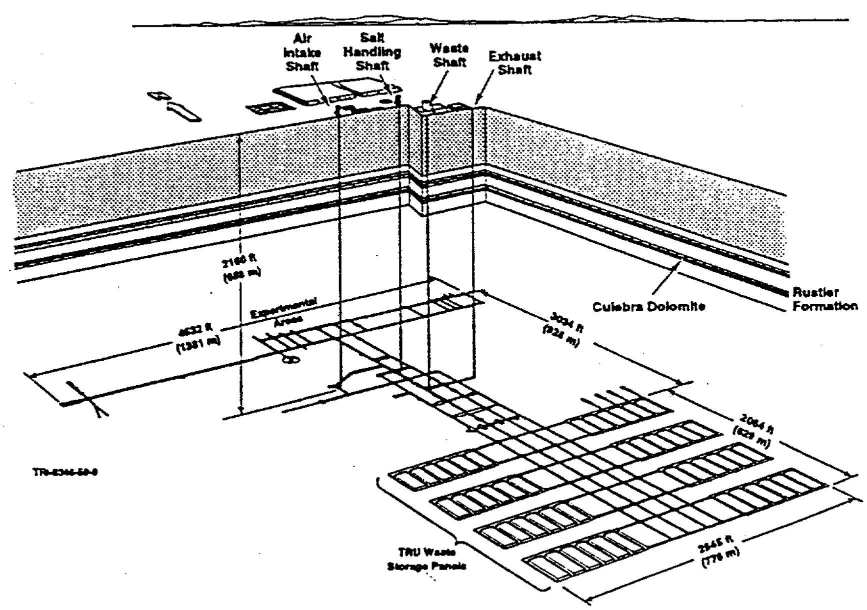

Figure 2: WIPP Repository, showing surface facilities, proposed TRU disposal areas, and experimental areas (after Nowak et al., 1990).

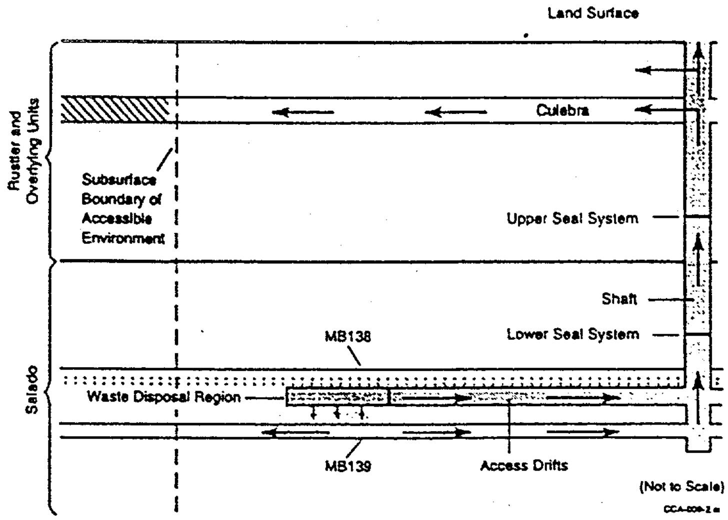

Figure 3: Conceptual release pathways for the undisturbed performance scenario.

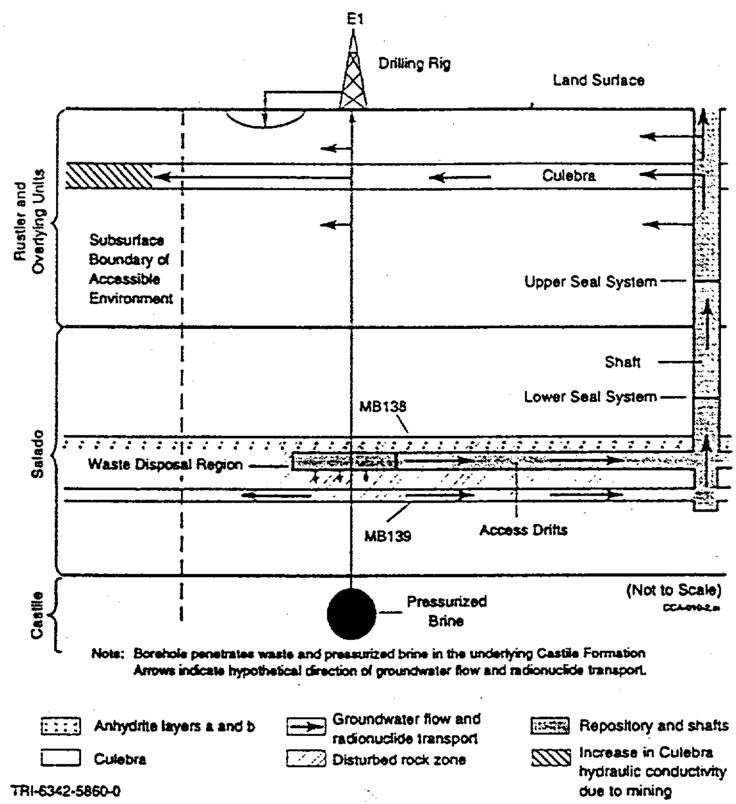

Figure 9: Conceptual release pathways for the disturbed performance deep drilling scenario.

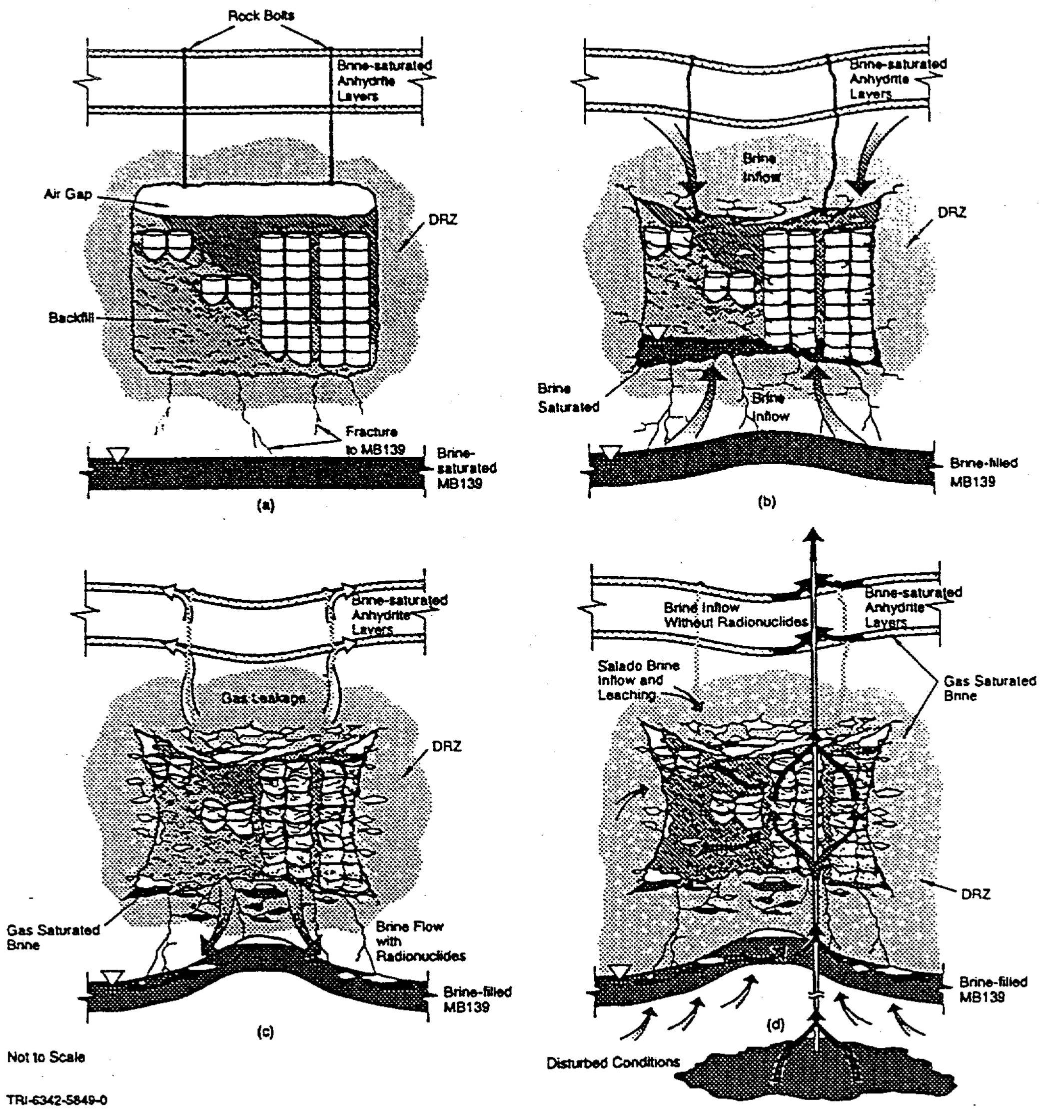

Figure 4: Conceptualization of processes occurring in the mined repository.

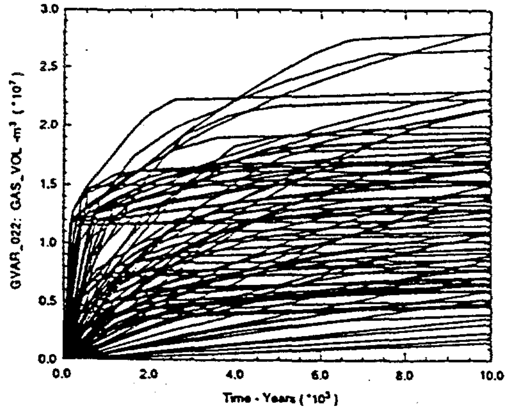

Figure 5: Volume of gas generated over 10,000 years (undisturbed scenario).

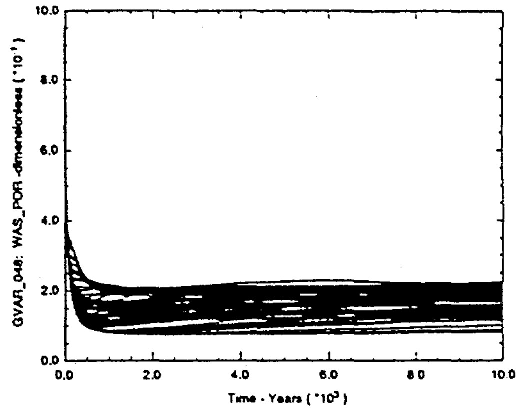

Figure 6: Reduction of porosity of mined area due to creep consolidation of Halite over 10,000 years (undisturbed repository).

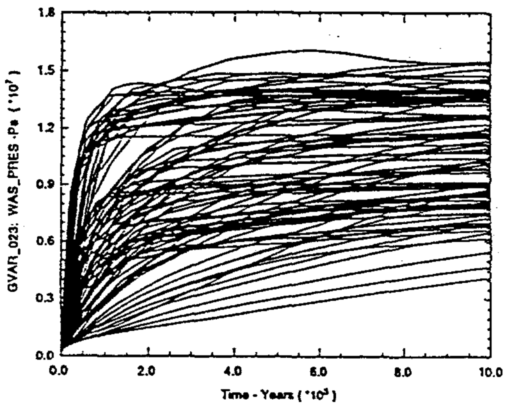

Figure 7: Pressure in the Repository (undisturbed Repository).

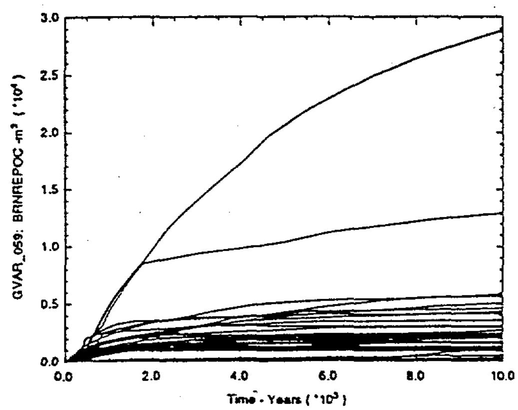

Figure 8: Cumulative flow of brine out of Repository 10,000 years (undisturbed Repository).

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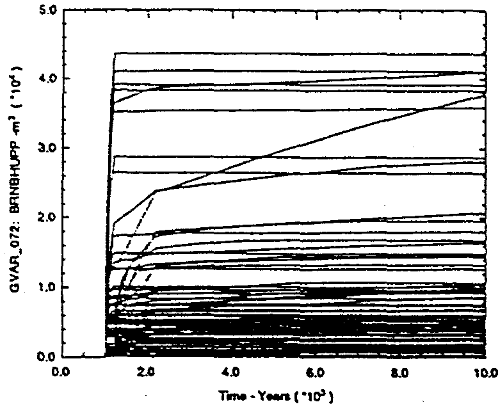

Figure 10: Cumulative flow of brine entering Repository from Brine Pocket over 10,000 years (human intrusion scenario).

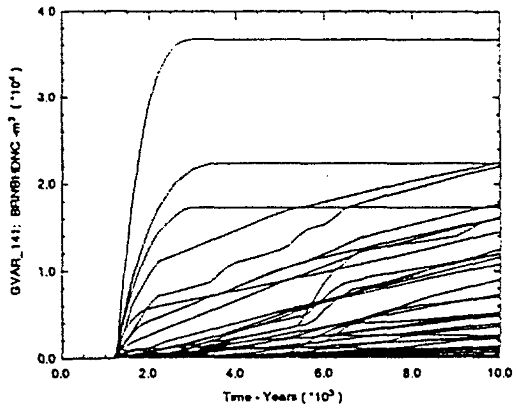

Figure 11: Cumulative flow of brine entering Repository from Dewey Lake Red Beds over 10,000 years (human intrusion scenario).

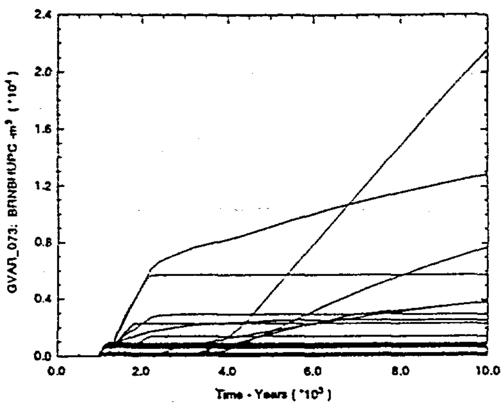

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Figure 12: Cumulative flow of brine up borehole out of Repository over 10,000 years (human intrusion borehole).

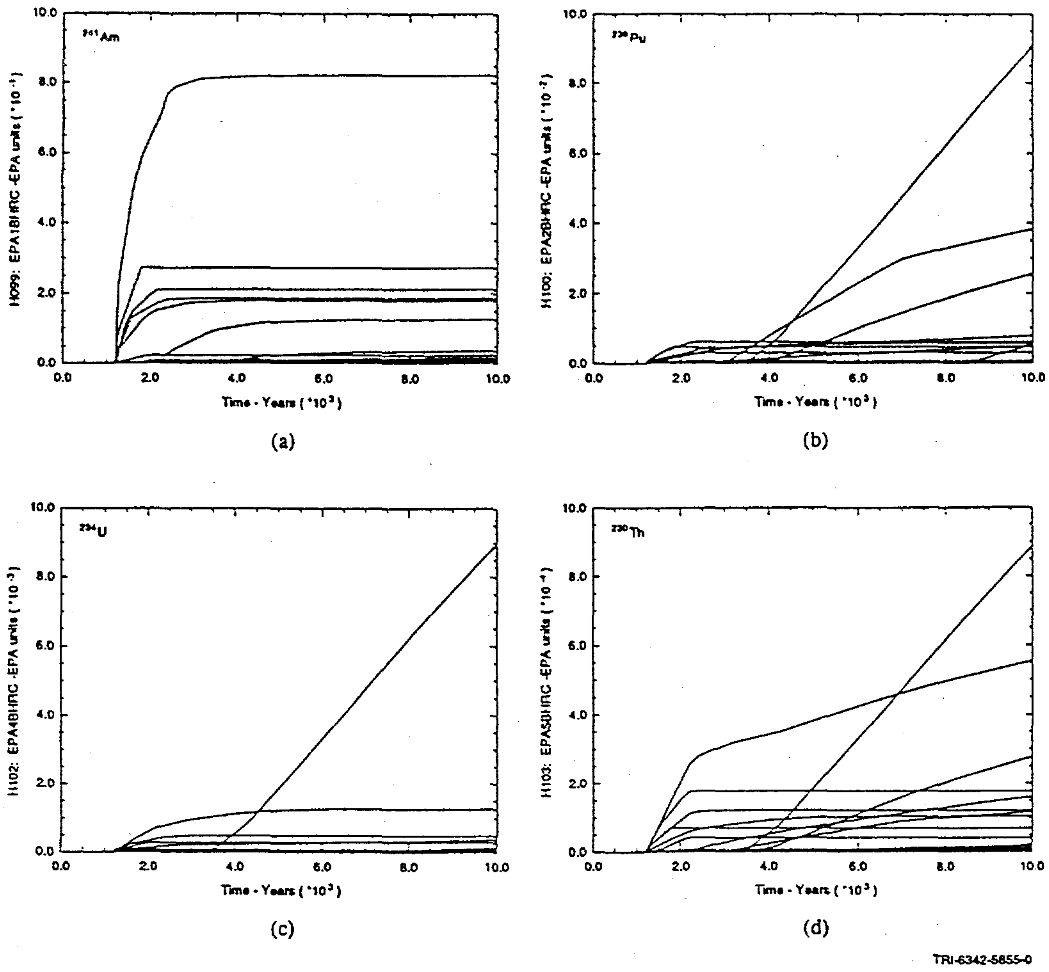

Figure 13: Cumulative release of four radionuclides to Culebra through borehole. (To convert to curies: multiply by 344 for Am, Pu, and U, and by 34.4 for Th. To convert to kg: multiply by 0.1 for Am, 5.54 for Pu, 55.06 for U, and 1.7 for Th.)

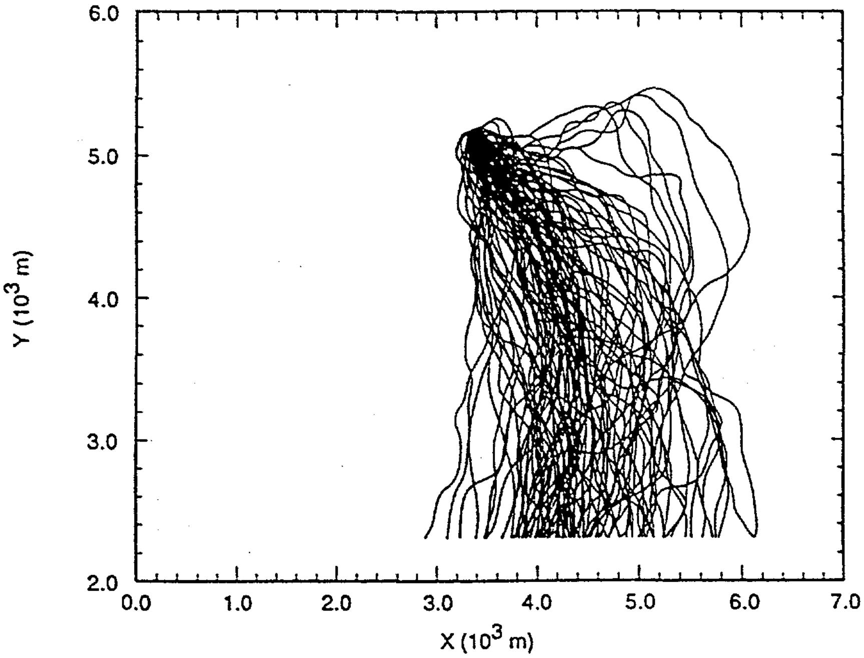

Figure 14: Flow Paths in Culebra.

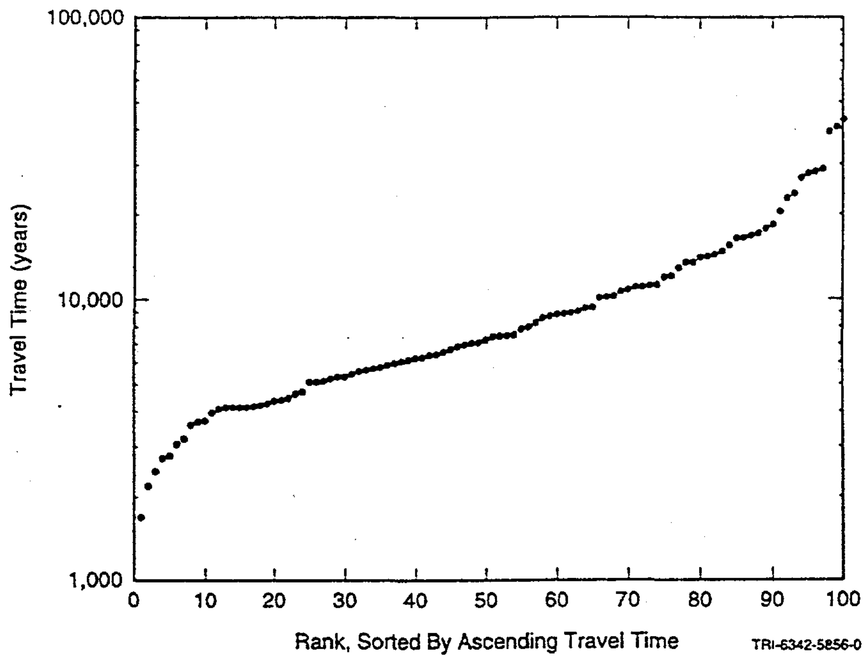

Figure 15: Travel Times for Flow Paths in Figure 14.

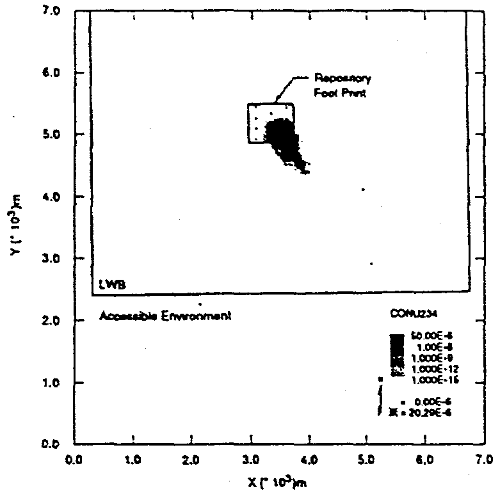

Figure 16(a): Time progression of U^{234} Plume through Culebra at 1000 years.

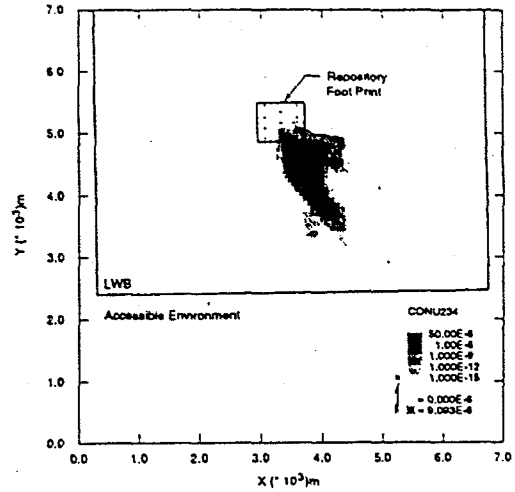

Figure 16(b): Time progression of U^{234} Plume through Culebra at 5000 years.

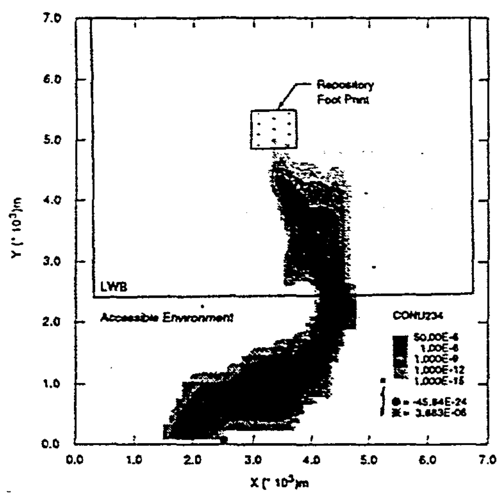

Figure 16(c): Time progression of U^{234} Plume through Culebra at 10,000 years.

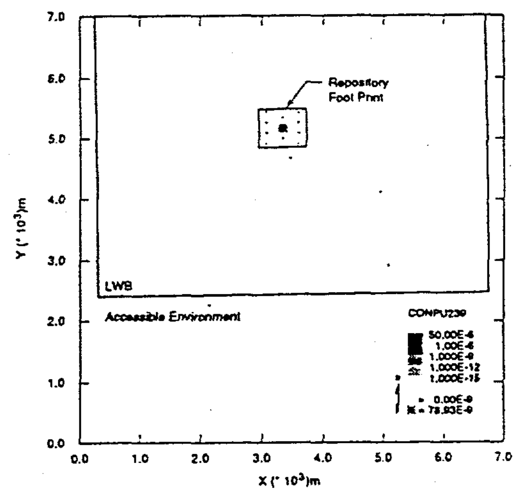

Figure 17: Pu^{239} Plume in Culebra concentration in kg/m^3 at 1000 years.

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8.0 REFERENCES

1) WIPP PA (Performance Assessment) Department, *Preliminary Performance Assessment for the Waste Isolation Pilot Plant, December 1992, Volume 2: Technical Basis.* SAND92-0700/2 (WPO#23528) Sandia National Laboratories, Albuquerque, NM., 1992.

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under contract DE-AC04-94AL85000.

2) WIPP PA (Performance Assessment) Department, *Preliminary Performance Assessment for the Waste Isolation Pilot Plant, December 1992, Volume 3: Model Parameters*. SAND92-0700/3 (WPO#23529) Sandia National Laboratories, Albuquerque, NM., 1992.

3) WIPP PA (Performance Assessment) Department, *Preliminary Performance Assessment for the Waste Isolation Pilot Plant, December 1992, Volume 4: Uncertainty and Sensitivity Analyses for 40 CFR 191, Subpart B*. SAND92-0700/4 (WPO#23599) Sandia National Laboratories, Albuquerque, NM., 1993.

4) WIPP PA (Performance Assessment) Department, *Preliminary Performance Assessment for the Waste Isolation Pilot Plant, December 1992, Volume 5: Uncertainty and Sensitivity Analyses of Gas and Brine Migration for Undisturbed Performance*. SAND92-0700/5 (WPO#23522) Sandia National Laboratories, Albuquerque, NM., 1993.

5) *Analysis Package for the Salado Flow Calculations (Task 1) of the Performance Assessment Analysis Supporting the Compliance Certification Application*, (WPO#40514), SWCF-a:1.2.07.4.1:WA:QA:CCA:Analysis Package For Salado Flow (Task 1), draft. Sandia National Laboratories, Albuquerque, NM.

6) *Analysis Package for the Salado Transport Calculations (Task 2) of the Performance Assessment Analyses Supporting the Compliance Certification Application (CCA), AP-023* (WPO#40515), SWCF-a:1.2.07.4.1:WA:QA:CCA:Analysis Package For Salado Transport (Task 2). Sandia National Laboratories, Albuquerque, NM.

7) *Analysis Package for the Culebra Flow and Transport Calculations (Task 3) of the Performance Assessment Calculations Supporting the Compliance Certification Application (CCA), AP-019* (WPO#40516), SWCF-a:1.2.07.4.1:WA:QA:CCA:Analysis Package For Culebra Flow and Transport Calculations of the PA Analysis Supporting the CCA:AP-019. Sandia National Laboratories, Albuquerque, NM.

8) United States Department of Energy, 1996. *Title 40 CFR Part 191 Compliance Certification Application for the Waste Isolation Pilot Plant*, Chapter 6: "Containment Requirements," DOE/CAO-1996-2184. U.S. Department of Energy, Carlsbad Area Office, Carlsbad, NM.

9) EPA (U.S. Environmental Protection Agency), 1985. *40 CFR Part 191: Environmental Standards for the Management and Disposal of Spent Nuclear Fuel, High-Level, and Transuranic Radioactive Wastes; Final Rule*, Federal Register, Vol. 50, No.182, pp. 38066 – 38089, September 19,1985. Office of Radiation and Air, Washington, DC.

10) *WIPP PA User's Manual for BRAGFLO, Version 4.00, Document Version 1.01*, WPO#30703, January 31, 1996, Sandia National Laboratories, Albuquerque, NM.

11) *WIPP PA User's Manual for NUTS, Version 2.02, Document Version 1.00*, WPO#37927, May 29, 1996, Sandia National Laboratories, Albuquerque, NM.

12) *WIPP PA User's Manual for SECOFL2D, Version 3.03, Document Version 1.01*, WPO#37271, May 7, 1996, Sandia National Laboratories, Albuquerque, NM.

13) *WIPP PA User's Manual for SECOTP2D, Version 1.30, Document Version 1.01*, WPO#36695, April 18, 1996, Sandia National Laboratories, Albuquerque, NM.