Presented at the TOUGH '95 Workshop, Lawrence Berkeley Laboratory, Berkeley, CA, March 20-22, 1995.

SAND95-0565C

The Effect of Stratigraphic Dip on Multiphase Flow at the Waste Isolation Pilot Plant

Stephen W. Webb and Kurt W. Larson
Sandia National Laboratories
Albuquerque, NM

Introduction

The Waste Isolation Pilot Plant (WIPP) is a U.S. Department of Energy research and development facility for the underground disposal of transuranic waste from U.S. defense-related activities. The WIPP repository is located within the Salado Formation, which is comprised of beds of pure and impure halite with thin interbeds of anhydrite and related clay seams. This formation is brine saturated with a pore pressure of approximately 12.5 MPa at the repository horizon. The Salado Formation dips gently southeast, on the average approximately 1°, with steeper dips locally. Elevated repository pressures, caused by gas generated as emplaced waste corrodes and degrades, may drive brine and gas out of the repository into the surrounding formation. Stratigraphic dip may cause increased brine inflow to the repository through countercurrent flow in the interbeds and enhanced gas migration distances in the updip direction due to buoyancy. Additional results are given by Webb and Larson (in press).

Overview of Two-Phase Flow Considerations

Stratigraphic dip can affect the fluid flow behavior along a flow path. Two flow conditions are possible, cocurrent flow in which both fluids (brine and gas) flow in the same direction and countercurrent flow in which the fluids flow in opposite directions. If only cocurrent flow is possible, brine inflow into the repository will stop when gas migrates from the room into the Salado Formation, reducing the amount of brine that flows into the repository and possibly limiting the amount of gas generated. If countercurrent flow occurs, brine will continue to flow into the repository while gas migration occurs, possibly increasing the amount of gas generated. In addition to affecting brine inflow, stratigraphic dip will impact gas migration behavior. Gas will preferentially migrate updip because the far-field pressure decreases with distance. In the updip direction, brine may flow into the repository, decreasing the flow resistance for gas migration. Similarly, gas migration downdip is much more difficult since the far-field pore pressure increases with distance.

Cocurrent and Countercurrent Flow

As detailed in Webb (in preparation), cocurrent and countercurrent flow regimes can be characterized by the Darcy velocities of the phases. Note that Darcy's Law predicts separate wetting (brine) and nonwetting (gas) phase velocities for a single flow path. Transition between cocurrent and countercurrent flow occurs when a phase velocity is zero, discounting the case where one or both of the fluids are immobile. Two transitions are possible, each involving a change in direction of one of the two fluids. Figure 1 shows the cocurrent and countercurrent flow regions along with a possible path of fluid velocities for the brine-inflow/gas-migration scenario in the updip direction, where the positive sign indicates flow towards the repository.

Starting from the left of the velocity path (Point A), gas (if present in the formation) and brine are flowing towards the repository. As the repository gas pressure increases, gas and brine flow towards the repository decrease, and the position on the velocity path moves upward and to the right. Eventually, the repository pressure increases sufficiently such that gas flow will be zero while some brine continues to flow slowly towards the repository (Point B). Moving yet further upward and to the right on the velocity path, gas pressure increases further such that gas flows away from the repository, while brine flow is zero (Point C). Between Points B and C, countercurrent flow will occur such that brine flows towards the repository while gas flows away. Continuing to the right, any additional increase in the gas pressure produces both brine and gas flow away from the repository.

Gas Migration

Consider a static column of water tilted at an angle θ as depicted in Figure 2a. Relative to location $x=0$, the water pressure changes with depth due to hydrostatic pressure. For illustration purposes, assume that the water pressure at 0 is 12.5 MPa. Also at location 0, suppose that gas is introduced at 12.6 MPa, and assume negligible capillary pressure. Because the gas is at a higher pressure, it will flow updip and downdip from location 0. Figure 2b shows the pressure variation for each fluid neglecting pressure drop due to flow. Since the gas has a lower density than water (or brine), the hydrostatic gradient is smaller. Gas will flow downdip a relatively short distance until the gas pressure is equal to the liquid pressure, which occurs at point a. Updip, however, the pressures never equalize, and the pressure difference between the gas phase and liquid phase continuously increases. While the distance is limited downdip, there is no limit to gas migration updip.

WIPP Simulations

Brine Inflow

Two-dimensional simulations of an isolated WIPP repository room have been performed using TOUGH2 for horizontal and 1° dipping stratigraphy similar to the geometry used in previous studies (Figure 3). The volume of the room changes with time due to salt creep through the pressure-time-porosity approach as described in Freeze et al. (1995). The room was located approximately midway between the top and bottom of the mesh. Two interbeds are in the model domain that extends laterally away from the room and are the preferential gas and brine flow paths away from the room. A simplified model for approximating the formation and propagation of fractures in the anhydrite interbeds due to high pore pressures was used. The simplified fracture model assumed that the anhydrite interbeds fracture when fluid pressures exceed the far-field fluid pressure by a specified amount, increasing interbed porosity and permeability. Increased interbed permeability decreased the resistance to brine and gas flow between the room and the interbeds, increasing flow away from the room and reducing the maximum room pressure. In addition, as discussed by Webb and Larson (in press), increased permeability increases the effect of countercurrent flow.

In both the dipping and horizontal simulations, fractures formed at about 300 years in the Upper Composite Interbed and in Marker Bed 139. The porosity and permeability of the interbeds increased significantly due to fracturing, creating more storage volume for gas and increasing lateral transmissivity. Before interbed fracturing, the amount of brine which flowed into the room was similar with and without dip. However, with dip, a second period of brine-inflow, due to countercurrent flow, occurred after fractures formed. This brine inflow was driven by the formation of a cell of countercurrent brine and gas that formed about 325 years after the start of the simulation (Figure 4a-4c) and continued until the end of the simulation. In that cell, gas flows up dip and away from the room, while brine flows down dip and towards the room. The volume of brine inflow due to countercurrent flow is of similar magnitude to the brine inflow occurring during room consolidation and pressurization as shown in Figure 4d. This countercurrent flow cell is associated with the leading edge of the zone of fractured rock in the Upper Composite Interbed. As the fractures propagate outward, the countercurrent flow cell follows. In these simulations, the cell has a maximum length of about 1500 m. The countercurrent flow cell appears to be a mechanism for redistribution of brine within the Upper Composite Interbed, that, when it is in close proximity to the room, provides brine inflow at a relatively high rate. The brine inflow rate due to countercurrent flow decreases as the countercurrent flow cell moves away from the room.

Gas Migration Distance

With the addition of dip and buoyancy effects, gas migration becomes a fully three-dimensional process. Except for geometry, the three-dimensional simulations used the same parameters as the two-dimensional simulations. Simulations were run to investigate gas migration in three dimensions with and without dip using mixed Brooks and Corey (Brooks and Corey, 1964) and van Genuchten/Parker (van Genuchten, 1980; Parker et al., 1987) two-phase characteristic curves as given in Webb (in press).

Figure 5 shows the gas-migration plumes and gas-saturation contours at 10,000 years. Figures 5a and 5b depict the effect of 1° dip using the mixed Brooks and Corey curves, while Figures 5c and 5d show the dip effect for van Genuchten/Parker. Without dip, the gas-migration plumes are approximately circular in shape and symmetrical about the room in both the upper and lower interbeds for both sets of two-phase curves. Deviations from a circular shape are due to the relatively crude nodalization employed. For mixed Brooks and Corey, the impact of stratigraphic dip is relatively small. In contrast, for van Genuchten/Parker, the shape of the plume of migrating gas is significantly different for 1° dip than for 0° dip. A teardrop shape forms in both interbeds, with significantly larger gas migration updip than downdip. Gas migrates three times as far for 1° dip than for 0° dip for van Genuchten/Parker.

Summary and Conclusions

The impact of dip on multiphase flow at the WIPP may be significant. With dip, an additional mechanism for brine inflow may occur, namely the formation of a cell of countercurrent brine and gas flow in the interbeds. The additional volume of brine inflow resulting from the countercurrent flow cell may be of similar magnitude to brine inflow without dip. Therefore, dip must be included in any repository model to include the countercurrent brine inflow mechanism. Gas migration may also be significantly influenced due to dip. Gas migration distances may increase dramatically with preferential migration updip.

Acknowledgment

This work was supported by the United States Department of Energy under Contract DE-AC04-94AL85000.

References

Brooks, R.H., and A.T. Corey (1964), "Hydraulic Properties of Porous Media," Hydrology Papers, No. 3, Colorado State University, March 1964.

Freeze, G.A., K.W. Larson, P.B. Davies, and S.W. Webb (1995), "Using a Multiphase Flow Code to Model the Coupled Effects of Repository Consolidation and Multiphase Brine and Gas Flow at the Waste Isolation Pilot Plant," *TOUGH '95 Workshop Proceedings*.

Parker, J.C., R.J. Lenhard, and T. Kuppusamy (1987), "A Parametric Model for Constitutive Properties Regarding Multiphase Flow in Porous Media," *Water Resour. Res.*, Vol. 23, No. 4, pp. 618-624, 1987.

van Genuchten, M.Th. (1980), "A Closed-form Equation for Predicting the Hydraulic Conductivity of Unsaturated Soils," *Soil Sci. Soc. Am. J.*, Vol. 44, pp. 892-898, 1980.

Webb, S.W. (in preparation), *Cocurrent and Countercurrent Flow in Porous Media As Implied by Darcy's Law for Unsaturated Flow.*

Webb, S.W. (in press), *Review of Two-Phase Characteristic Curves for Porous Media and Application to the WIPP*, SAND93-3912, Sandia National Laboratories.

Webb, S.W. and K.W. Larson (in press), *The Effect of Stratigraphic Dip on Brine Inflow and Gas Migration at the Waste Isolation Pilot Plant*, SAND94-0932, Sandia National Laboratories.

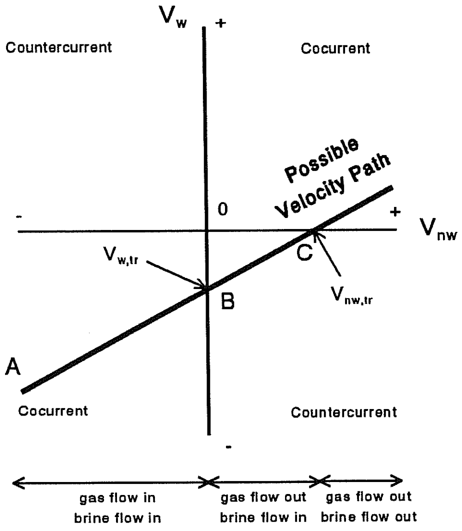


Figure 1
Two-Phase Flow Map

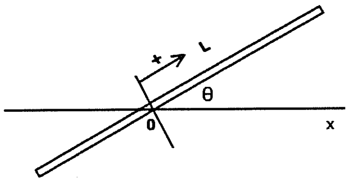


Figure 2a
Tilted Water Column

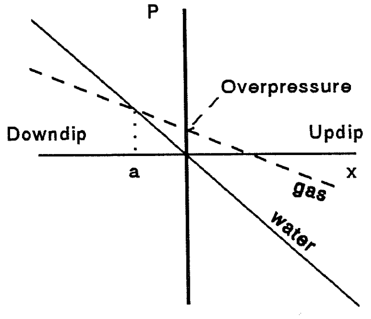
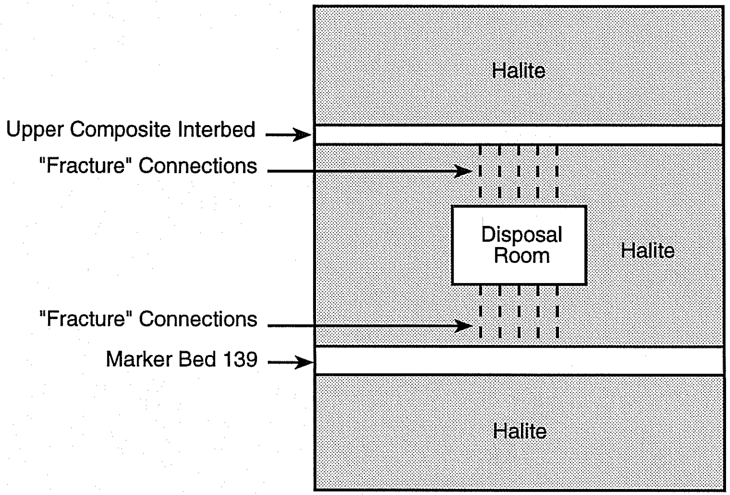
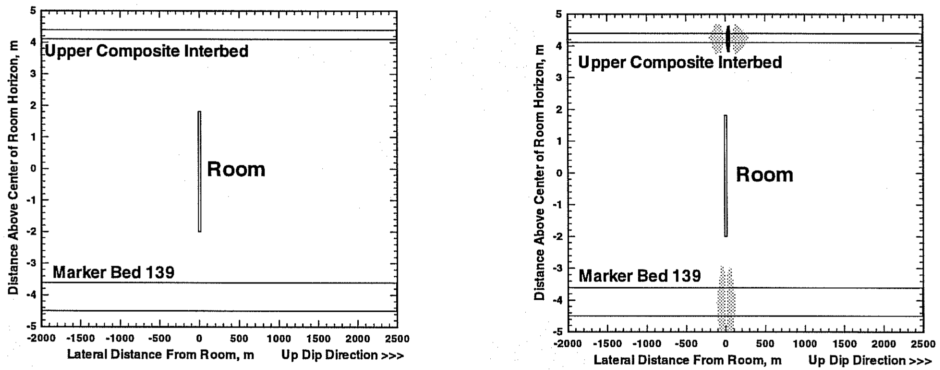


Figure 2b
Water and Gas Pressure Variation



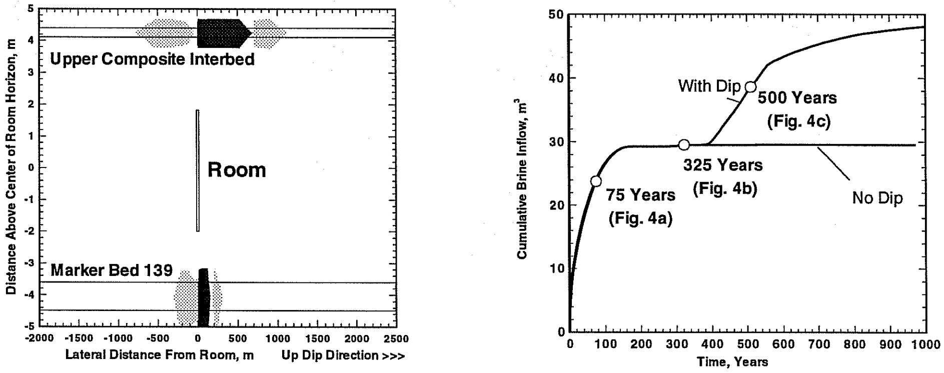
Not to Scale

Figure 3
Conceptual Model



a) Flow Conditions at 75 Years with Dip
(Brine Inflow, Gas Inflow)

b) Flow Conditions at 325 Years with Dip
(Small Brine Inflow, Gas Outflow)

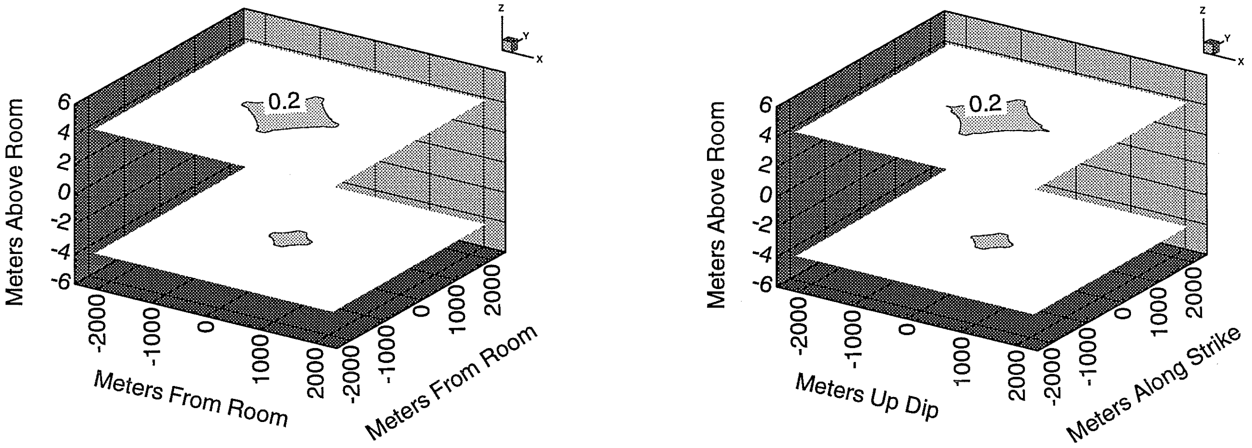


c) Flow Conditions at 500 Years with Dip
(Fracturing Stimulates Countercurrent Flow)

d) Brine Inflow With and Without Dip

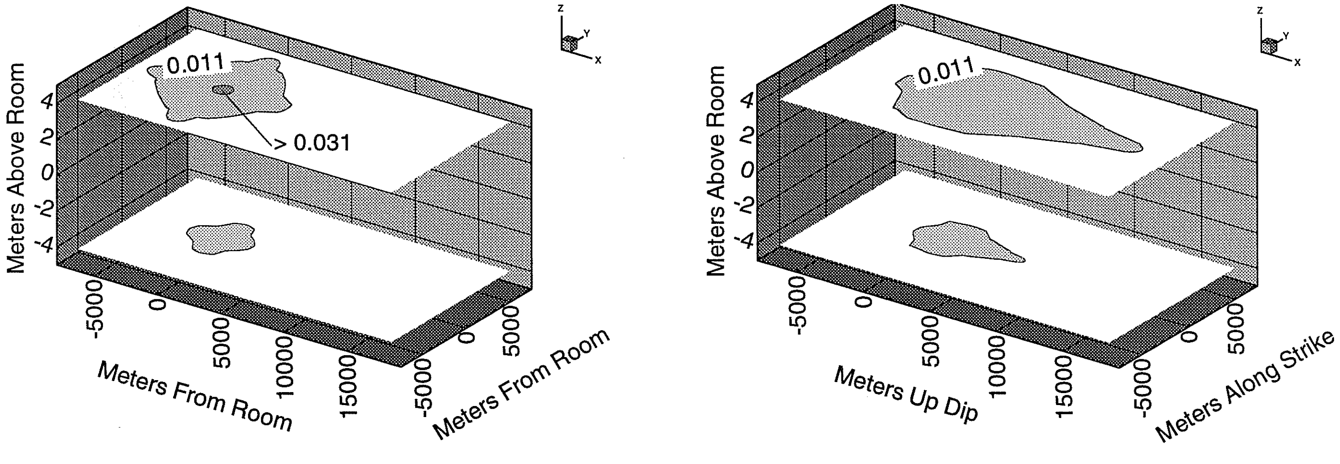
Figure 4
Effect of Dip on Brine Flow Mechanisms

Black	- countercurrent flow
Grey	- cocurrent flow
White	- gas immobile



a) Brooks and Corey - No Dip

b) Brooks and Corey - 1 degree dip



c) van Genuchten/Parker - No Dip

d) van Genchten/Parker - 1 degree dip

Figure 5
Effect of Dip on Gas-Migration Plumes and Gas-Saturation Contours