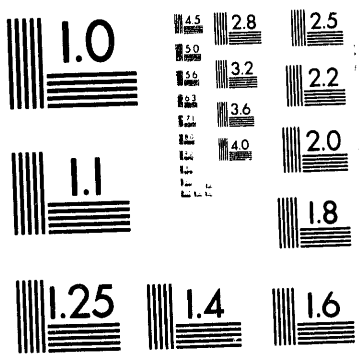
1.0
4.5
2.8
2.5
5.0
3.2
2.2
5.6
6.3
3.6
2.0
4.0
1.1
1.8
1.25
1.4
1.6

1 of 1

DOE/WIPP--91-047C
Conf-920307--101

FLUID FLOW THROUGH VERY LOW PERMEABILITY MATERIALS: A CONCERN IN THE GEOLOGICAL ISOLATION OF WASTE

Dwight E. Deal
International Technology Corporation
5301 Central Avenue, N.E., Suite 700
Albuquerque, NM 87108

ABSTRACT

The geological isolation of waste usually involves the selection of sites where very low permeability materials exist, but there are few earth materials that are truly impermeable. Regulatory concerns for the containment of radioactive material extend for geologic periods of time (i.e., 10,000 years or more), and it becomes nearly impossible to "assure" the behavior of the site for such long periods of time. Experience at the Waste Isolation Pilot Plant (WIPP) shows that very slow movements of fluid can take place through materials that may, in fact, have no intrinsic permeability in their undisturbed condition. Conventional hydrologic models may not be appropriate to describe flow, may provide modeling results that could be in significant variance with reality, and may not be easy to defend during the compliance process. Additionally, the very small volumes of fluid and very slow flow rates involved are difficult to observe, measure, and quantify.

The WIPP disposal horizon is excavated 655 m below the surface in bedded salt of Permian age. Salt has some unique properties, but similar hydrologic problems can be expected in site investigations were other relatively impermeable beds occur, and especially in deep sites where significant overburden and confining pressures may be encountered. Innovative techniques developed during the investigations at the WIPP may find utility when investigating other disposal sites.

The details of flow in these very low permeability units is quite complex and difficult to quantify. Vertical drillholes yield inconsistent data, even when closely spaced, but horizontal drillholes provide consistent and comparable data sets. Flow may be constrained to a relatively few, fairly discrete, bedding planes and radial flow (as assumed in most modeling) toward an excavation or drillhole may not occur. Fluid preferentially occurs in the more argillaceous beds and is not uniformly distributed throughout the salt. The pore spaces in some units may be so small that surface tension forces become significant and Darcy's Law may have to be applied in a modified form or may not hold at all. Additionally, some previously unsuspected flow mechanism may be acting, such as compaction in the pillars driving brine out of poorly compacted clays.

Ongoing work at the WIPP is expected to continue to advance understanding of flow through very low permeability materials. The study of flow under these conditions will become increasingly important as additional waste disposal sites are designed that require assurance of their safety for geological periods of time.

Work supported by the U.S. Department of Energy
under DOE Contract No. DE-AC04-86AL31950
DOE-WIPP 91-047C

The geological isolation of waste usually involves the selection of sites where very low permeability materials exist, but there are few earth materials that are truly impermeable. Regulatory concerns for the containment of radioactive material extend for geologic periods of time (a mandated 10,000 years). The study of ground water and the engineering aspects of hydrogeology have traditionally focused on ground water as a resource (1, 2). As a result, the focus has been on the conditions of flow where the quantity and quality of the water available are adequate for human use and the materials containing the water allow it to flow (or be induced to flow) rapidly enough so that useful quantities can be produced in reasonable amounts of time.

Disposal sites are usually chosen on (or in) materials with very low permeability for which conditions of flow are less well understood. In order to predict the long term behavior of any such disposal site, we must first have experience with and an understanding of the detailed behavior of the systems acting at the disposal site. Uncertainties in the prediction of repository behavior can be significantly reduced by continued site investigations, but can never completely be eliminated. For these and other reasons, the National Research Council (3) concluded that science cannot "prove" (in an absolute sense) that a disposal site will be "safe" as defined by existing Environmental Protection Administration standards and United States Nuclear Regulatory Commission regulations.

Numerous recent studies have demonstrated that describing flow under low permeability conditions stretch the limits of our knowledge for shales (4, 5, 6), clays (7, 8), unsaturated fractured rock (including shales, clays, tuff, and basalts)(9), and evaporites (10, 11). Recent experience at the Waste Isolation Pilot Plant (WIPP) shows that very slow movements of fluid can take place through materials that may, in fact, have no intrinsic permeability in their undisturbed condition. Conventional hydrologic models may not be appropriate to describe flow (12), may provide modeling results that could be in significant variance with reality, and may not be easy to defend during the compliance process. Additionally, the very small volumes of fluid and very slow flow rates involved are difficult to observe, measure, and quantify.

The WIPP disposal horizon is excavated 655 m below the surface in bedded salt of Permian age. Considerable stratigraphic variations occur within the salt beds. Although dominantly halite, individual units range from clear halite through argillaceous halite to polyhalitic halite. Interbeds include clay seams and anhydrite beds. Water is present in several ways within the Salado Formation (11): (1) within hydrous minerals such as gypsum and clays, (2) as fluid inclusions within halite and other crystals, (3) within intergranular pores and open fractures, and (4) as intergranular moisture within poorly consolidated clays which occur within salt crystals as well as between halite, anhydrite, and other crystals.

The undisturbed clear halite units may be effectively impermeable. State-of-the-art permeability testing (13, 14) was unable to measure any permeability, indicating that if it exists at all, intrinsic permeability of the clear halite units is less than 1×10^{-23} m^2 (0.01 nanodarcy). Those halite units that contain a few percent clay are more permeable, typically less than 1×10^{-20} m^2 (10 nanodarcy). The permeability of the interbedded anhydrite units are several orders of magnitude greater, typically between 1×10^{-19} and 1×10^{-18} m^2.

Salt has some unique properties, including the fact that at repository depths it deforms plastically. Studies undertaken during the Brine Sampling and Evaluation

Program (BSEP) at the WIPP (15, 16, 17, 18, 19, 20, 21) were directed primarily toward the environment in and directly adjacent to the underground excavations. These studies and others (22, 23, 24, 25) show that the rock immediately surrounding the excavation is altered significantly from its original state due to the influence of deformation induced by the rock excavation and the movement of salt toward the excavation. The common theme running through the BSEP investigations relates to the presence and movement of brine in rocks that saw little to no fluid migration prior to the development of deviatoric stress accompanying excavation and the permeability enhancement caused by elastic expansion and brittle deformation of the salt and anhydrite units. A halo of deformation forms around the excavations, whether they are rectangular or circular in cross section.

The development of this halo of deformation around an underground excavation at the WIPP, sometimes described as the Disturbed Rock Zone (DRZ), is discussed by Deal and Roggenthen (11). They pointed out that previous discussions do not make it adequately clear that there are generally two parts to the deformational envelope around underground excavations in salt: an outer zone where dilatency and microfracturing occur with pore pressures above atmospheric (zone C in Fig. 1), and an inner zone characterized by macrofracturing and pore spaces where the pressures are essentially at atmospheric (zone B in Fig. 1). Some authors tend to treat the inner zone, which includes the volume of rock that has separated (decoupled) from the host rock, as simply a growing part of the excavation comprising the "Actual Opening" (26). Brine moving toward the excavation behaves differently in these two zones, and it is important to consider both of them when discussing brine seepage into the WIPP excavations.

The salt at the WIPP originated as a stratified and bedded sedimentary rock and consists of alternating sequences of halite, argillaceous halite, polyhalitic halite, clay layers, and thin anhydrite beds. As a result, there are numerous horizontal discontinuities. There are clay partings and thin (1-3 cm) clay beds, as well as beds of anhydrite ranging from a few millimeters to a meter or so in thickness. The anhydrite beds are brittle and do not deform plastically at repository depths. Typical storage rooms are 4m (13 ft) high, and 10m (33 ft) wide. Therefore, the deformational sequence is complicated by the effects of geometry and the stratigraphy as the disturbed envelope is driven toward a circular geometry (Fig. 2).

Evidence is abundant that the excavation geometry around the openings at the WIPP is modified by these discontinuities and inhomogeneties. It includes failure of roof and floors due to heaving, separation along clay seams, and the development of macrofractures in ribs (11, 22, 25). The patterns of fracturing and deformation observed at the WIPP is shown in Fig. 3.

The details of flow in these very low permeability units is quite complex and difficult to quantify. Vertical drillholes yield inconsistent data, even when closely spaced, but horizontal drillholes provide consistent and comparable data sets (21). Flow may be constrained to a relatively few, fairly discrete, bedding planes and radial flow (as assumed in most modeling) toward an excavation or drillhole may not occur (21). Fluid preferentially occurs in the more argillaceous beds and is not uniformly distributed throughout the salt (18). The pore spaces in some units may be so small that surface tension forces become significant and Darcy's Law may have to be applied in a modified form, such as the piece-wise method suggested by Deal and others (18), or may not hold at all.

Additionally, some previously unsuspected flow mechanism may be acting, such as compaction in the pillars driving brine out of poorly compacted clays (18).

A number of modeling efforts have been made in an attempt to predict seepage into the WIPP excavations. Seepage into a horizontal drillhole 7.6 cm (3 in) diameter and 46 m (150 ft) long is predicted to be on the order of 0.01 liters per day if a permeability of 1×10^{-22} m^2 (0.1 nanodarcy) is used for the undisturbed salt. Three drillholes of that dimension have been monitored for over 2 years and all three accumulate fluids at seepage rates on the order of 0.01 to 0.02 liters per day.

The way in which flow rate varies with time is important. If flow rate eventually reaches at a steady rate, then there may be some far-field brine that flows through the body of the undisturbed rocks to reach the repository excavations. If flow rate continues to decrease and eventually ceases (21), then there is no significant amount of brine derived from the far-field and only brine released from the disturbed rock zone due to depressurization will enter the repository excavations. Observations are presently being made at the WIPP to determine which of these conditions exist.

If no far-field flow exists and radial flow occurs in all directions toward a waste storage room, then release of brine from the disturbed rock zone around the excavations due to depressurization is estimated to produce about 150,000 liters of brine (21). This volume is on the same order of magnitude as the volume of brine (220,000 liters) necessary to corrode all the metal in the waste and waste storage drums (21). Corrosion will consume brine and produce gas. If the volume of brine entering the repository is less than that required to completely corrode the metal, then all the brine that comes in contact with metal will be consumed.

As pointed out above, there is good evidence that the assumption of radial flow may not hold for the WIPP. The undisturbed clear halite units have such low permeability (or none at all) that flow is probably constrained and only occurs horizontally, parallel to bedding. In that case less than one tenth of the 150,000 liters estimated above may enter the repository to react with the metal stored there. If compaction of the clays is the source of the brine rather than release of brine from the disturbed rock zone due to depressurization, then even less brine may enter the repository.

Continued site investigations at the WIPP are defining the bounds of the brine seepage phenomena. After extensive modeling, field investigations, and experiments, some uncertainties still exist. Although the details of flow in the geologic units at the WIPP are quite complex and difficult to quantify, it is clear that only very small quantities of brine moving very slowly are involved. Although field investigations show that very little brine actually enters the excavations (see BSEP references cited previously), it is impossible to completely eliminate all uncertainty. The fact that some uncertainties remain should not be the same as determining whether or not the relative risk of transporting this waste to the WIPP and disposing of it there is less (and more acceptable to society) than leaving it where it is or disposing of it in some other way.

REFERENCES CITED

1. Dommenico, P. A. and F. W. Schwartz, 1990, Physical and Chemical Hydrogeology: John Wiley and Sons, New York, 824 pp.

2. Freeze, R. A., and J. A. Cherry, 1979, Groundwater: Prentice-Hall, Inc., Englewood Cliffs, N.J., 604 pp.

3. National Research Council, 1990, Rethinking High-Level Radioactive Waste Disposal, A Position Statement of the Board on Radioactive Waste Management, Commission on Geosciences, Environment, and Resources: National Academy Press, Washington, D.C., 34 pp.

4. Neuzil, C. E., 1988, Ground-Water Flow in a Cretaceous Shale: Ground Water, V. 26, No. 6, p. 784

5. Toran, L., 1988, Long-Term Versus Short-Term Slug Tests in Low Permeability Formations: Ground Water, V. 26, No. 6, p. 787.

6. Bentley, M. E., K. Karasaki, and M. A. Balderman, 1988, Drill-Stem Testing and Analysis in Fractured Shale at a Hazardous Waste Management Facility, Northern California: Ground Water, V. 26, No. 6, p. 787-788.

7. Cherry, J. A., 1988, Field Studies of Fractured and Unfractured Clay: Ground Water, V. 26, No. 6, p. 783.

8. Barbour, S. L., 1988, Mechanisms for Transient Ground-Water Flow Due to Osmotic Effects: Ground Water, V. 26, No. 6, p. 783

9. Evans, D. D., and T. J. Nicholson, (eds.) 1987, Flow and Transport through Unsaturated Rock: American Geophysical Union, Geophysical Monograph No. 42, 187 pp.

10. Kreitler, C. W., 1988, Integrated Hydrologic-Geochemical Studies for Characterization of Low-Permeability Settings: Ground Water, V. 26, No. 6, p. 83-784.

11. Deal, D. E., and W. M. Roggenthen, 1991, Evolution of Hydrologic Systems and Brine Geochemistry in a Deforming Salt Medium: Data from WIPP Brine Seeps, Proceedings of Waste Management '91, Vol. II, Tucson, AZ, p. 507-516.

12. Organization for Economic Co-Operation and Development, 1991, The International Hydrocoin Project, Groundwater Hydrology Modeling Strategies for Performance Assessment of Nuclear Waste Disposal, Level 3: Uncertainty and Sensitivity Analysis: Organization for Economic Co-Operation and Development, Paris, 336 pp.

13. Beauheim, R. L., and R. M. Holt, 1990, Hydrogeology of the WIPP Site, in Powers, D., N. Rempe, R. Holt, and R. L. Beauheim, 1990, Geological and Hydrological Studies of Evaporites in the Northern Delaware Basin for the Waste Isolation Pilot Plant (WIPP), New Mexico; Geological Society of America, Field Trip No. 14 Guidebook, Geol. Soc. Am. 1990 Annual Meeting, Dallas, Texas.

14. Beauheim, R. L., and S. Howarth, 1991, Status of Room Q Experiments and Salado Permeability Tests: Presentation to the National Academy of Sciences, WIPP Review Panel, June 4, 1991, Albuquerque, NM.

15. Deal, D. E. and J. B. Case, 1987, Brine Sampling and Evaluation Program, Phase I Report: DOE/WIPP 87-008, prepared for the U.S. Department of Energy by International Technology Corporation and Westinghouse Electric Corporation, Carlsbad, NM, 163 p.

16. Deal, D. E., J. B. Case, R. M. Deshler, P. E. Drez, J. Myers, and J. A. Tyburski, 1987, Brine Sampling and Evaluation Program, Phase II Report: DOE/WIPP 87-010, prepared for the U.S. Department of Energy by International Technology Corporation and Westinghouse Electric Corporation, Carlsbad, NM, 193 p.

17. Deal, D. E., 1988, Brine Seepage into the Waste Isolation Pilot Plant (WIPP) Excavation: Proceedings of Waste Management '88, Vol. II, Tucson, AZ, p. 649-657.

18. Deal, D. E., R. J. Abitz, D. S. Belski, J. B. Clark, M. E. Crawley, M. L. Martin, 1989, Brine Sampling and Evaluation Program, 1989 Report, DOE/WIPP-91-009, prepared for the U.S. Department of Energy by International Technology Corporation and Westinghouse Electric Corporation, Carlsbad, New Mexico.

19. Deal, D. E., and W. M. Roggenthen, 1989, The Brine Sampling and Evaluation Program (BSEP) at WIPP: Results of Four Years of Brine Seepage Data, Proceedings of Waste Management '89, Vol. I, Tucson, AZ, p. 405-406.

20. Deal, D. E., R. J. Abitz, J. B. Case, M. E. Crawley, R. M. Deshler, P. E. Drez, C. A. Givins, R. B. King, B. A. Lauctes, J. Myers, S. Niou, J. M. Pietz, W. M. Roggenthen, J. R. Tyburski, M. G. Wallace, and D. S. Belski, 1989, Brine Sampling and Evaluation Program, 1988 Report, DOE/WIPP-89-015, prepared for the U.S. Department of Energy by International Technology Corporation and Westinghouse Electric Corporation, Carlsbad, New Mexico.

21. Deal, D. E., R. J. Abitz, D. S. Belski, J. B. Case, J. B. Clark and M. L. Martin, 1992, Brine Sampling and Evaluation Program, 1990 Report, DOE/WIPP-91-036, prepared for the U.S. Department of Energy by International Technology Corporation and Westinghouse Electric Corporation, Carlsbad, New Mexico.

22. Bechtel National, Inc., 1986, Interim Geotechnical Field Data Report; DOE/WIPP 86-012, prepared for the U.S. Department of Energy by Bechtel National, Inc., San Francisco, California.

23. Borns, David J., and John C. Storemont, 1988, An interim report on excavation effect studies at the Waste Isolation Pilot Plant: The delineation of the disturbed rock zone: SAND87-1375, a report prepared for the U.S. Department of Energy by Sandia National Laboratories, Albuquerque, New Mexico, 30 p.

24. Francke, C., R. Carrasco, R. Cook, D. Deal, R. Deshler, and R. Williams, 1989, Geotechnical Field Data and Analysis Report, July 1987 - June 1988; DOE/WIPP 89-009, prepared for the U.S. Department of Energy by Westinghouse

Electric Corporation and International Technology Corporation, Carlsbad, New Mexico, 2 Vol.

25. Francke, C., S. Carlisle, E. Lewis, and N. Rempe, 1990, Geotechnical Field Data and Analysis Report, July 1988 - June 1989; DOE/WIPP 90-006, prepared for the U.S. Department of Energy by Westinghouse Electric Corporation and International Technology Corporation, Carlsbad, New Mexico, 2 Vols.

26. Mraz, D., 1980, Plastic behavior of salt rock utilized in designing a mining method, CIM Bulletin, 73, p. 11-123.

02052

FIGURE CAPTIONS

Figure 1

Diagramatic cross-sections of a rectangular excavation in homogeneous salt one day and two years after mining. Zone A is the mined opening, Zone B is the zone of macrofracturing with pore pressures at atmospheric, Zone C is the zone of plastic deformation with pore pressures increasing from atmospheric to lithostatic, and Zone D is undisturbed salt witn pressures at lithostatic. The Distrubed Rock Zone is composed of both Zone B and Zone C.

Figure 2

Diagrammatic cross section of a WIPP storage room in bedded salt approximately six years after mining. Zones A, B, C, and D are the same as in Fig. 1.

Figure 3

Diagrammatic cross section of fracturing observed around a WIPP four- by eleven-meter room five years after mining.

DATE
FILMED
1/12/94
END