EVOLUTION OF HYDROLOGIC SYSTEMS AND BRINE GEOCHEMISTRY IN A DEFORMING SALT MEDIUM: DATA FROM WIPP BRINE SEEPS*

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ABSTRACT

Measurement of brine seepage into the Waste Isolation Pilot Plant (WIPP) is important from the standpoint of evaluation of the environment in which transuranic (TRU) radioactive waste will eventually reside. Data on brine seepage and related phenomena have been gathered since 1982, and it has been a major challenge to make accurate estimates of volumes and compositions. The volumes of brine involved are quite small and the rate of seepage is slow (on the order of 200 ml into a drillhole 15 meters long over a month-long period). Additionally, at repository depths (655 m), the layered salt bedrock (Salado Formation of Permian age) deforms plastically, flowing into the repository excavations, changing porosity and permeability with time.

INTRODUCTION

Five hypotheses for the possible brine flow regime at the WIPP have been suggested:

1. A far-field source exists for the fluids that form the brine. This hypothesis assumes that the salt can be modeled as an elastic solid supporting overburden. This is the case with "normal" water-bearing units; the salt has a very low, but real interconnected far-field porosity and permeability (on the order of 1.5 percent and one nanodarcy, respectively). Brine slowly moves through the body of the Salado Formation.
2. A far-field source exists with flow enhanced close to the excavations by the dilatancy of the salt as it flows plastically into the excavations. Preliminary modeling suggests that the pore spaces in the zone of dilatancy will increase faster than brine can fill them, and the zone around the excavation will support multi-phase flow.
3. Near-field flow only with no contribution of brine from the far field. This hypothesis assumes that for all practical purposes the salt in the far field is impermeable and that brine (along with gas and salt) only moves in the zone of dilatancy around the excavations where porosity and permeability have been enhanced by deformation of the salt, driven toward the excavation openings by deviatoric stress that results from the creation of the openings by mining.
4. Most of the brine flows along more conductive interbeds (anhydrite layers, bedding planes, clay seams, or other stratigraphic partings) while little or no brine flows through fairly pure halite. This would modify both near-field and far-field hypotheses.
5. A compaction drive is present within the salt that squeezes brine out of undercompacted clays. This hypothesis assumes that lithostatic loading in the pillars between the excavated rooms can drive moisture out of the clays, along generally horizontal flow paths, to the excavations.

The brine contains dissolved gas (mostly nitrogen) that exsolves as the confining pressure is lowered. This gas is an additional driving mechanism for the brine movement, especially in the first few days and weeks following mining. Gas drive locally may modify flow under all five of the above described conditions.

It is difficult to conceive of intrinsic permeability in a plastic medium under high confining stress. Our current thinking favors interbed flow and compaction drive in combination with movement under deviatoric stress present in the zone of dilatancy, with an initial gas-drive component during the first few months following excavation. If this is possible, then the brine seepage is a direct result of excavating the repository shafts, drifts, and rooms. This implies a near-field, probably self-limiting, phenomenon.

The chemistry of the naturally-occurring brines has been modified by several processes. Evaporation into the repository atmosphere increases the relative proportions of magnesium and potassium. Additionally, operational activities such as spreading water to aid in floor consolidation, have locally altered the composition of the brines found in some drillholes. Consistent compositions have been

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obtained from a small suite of drillholes where evaporation and contamination do not appear to be a problem.

Major element composition of these brines suggests that they originated from seawater that had precipitated halite, modified by diagenetic reactions with gypsum, magnesite, and polyhalite; and by ion-exchange with clay minerals. A high magnesium and bromine content argue strongly that these originated as residual fluids, not as infiltrating groundwater that subsequently dissolved salt. Additionally, the composition of fluid inclusions differs from the nearby brine seeps, suggesting no mixing and little movement of the brines.

The rock-brine equilibrium was determined using the EQ3NR code. The brine was saturated with respect to anhydrite, barite, fluorite, glauberite, gypsum, and halite. Some samples were saturated with respect to celestite, dolomite, magnesite, and polyhalite. This provides evidence for WIPP brines originating as intergranular fluids that equilibrated with evaporite salts.

This does not unequivocally rule out a far-field source for the brine, but if there has been large-scale fluid movement through the Salado Formation, then the time-scale was greater than the time required for diagenetic reactions to produce magnesite, polyhalite, and quartz.

As the excavations age, fractures develop around the openings, interdicting the flow of brine to the excavation surface. The brine seepage is channeled downward into floor fractures. As a result, holes drilled downwards typically yield much more brine than shallow holes drilled upwards or into the sides of the excavations.

INTRODUCTION

The data supporting this summary and discussion report were obtained between 1982 and 1988 at the WIPP. The data was reported in a number of project documents including Black and others (1983), TSC-D'Appolonia (1983a), TSC-D'Appolonia (1983b), Alcorn (1983), Morse and Hassinger (1985), Stein and Krumhansl (1986), Nowak (1986), Deal and Case (1987), Deal and others (1987), Nowak and McTigue (1987), Deal (1988), Nowak and others (1988), Lappin (1988), Stein and Krumhansl (1988), Deal and Roggenthen (1989), and Deal and others (1989). The Brine Sampling and Evaluation Program (BSEP) is a formalized continuation of studies that began in 1982 as part of the Site Validation Program. The program was established in 1985. The mission was to document and investigate the origins, hydraulic characteristics, extent, and composition of brine occurrences in the Permian Salado Formation and the seepage of that brine into the WIPP excavations (Morse and Hassinger, 1985). This document focuses on the cumulative data obtained from the BSEP.

The overall activities of the BSEP described and quantified the brine. It includes documentation and study of brine inflow into boreholes in the facility. The BSEP investigated the occurrence and development of brine weeps, crusts, and brine geochemistry. The presence of salt-tolerant bacteria in the workings was recorded and their possible interactions with experiments and operations, was assessed. The formation properties associated with the occurrence of brine was characterized. The determination of formation properties included the water content of various geologic units, direct examination of these units in boreholes using a video camera system, and measurement of electrical properties relatable to the brine contents. Modeling examined the interaction of salt deformation near the workings and the flow of brine through the deforming rocks.

OBSERVATIONS AND DATA

Monitoring of Brine Inflow Parameters

The distribution of relative amounts of brine seepage between upholes in the back (roof) of the excavations, downholes in the floor, and horizontal holes in the ribs (walls) has been described by Nowak (1986), Deal and Case (1987), Deal and others (1987), and Deal and others (1989). Boreholes (15 meters long) show upholes in the back produced much smaller amounts of brine than the downholes and tend to cease brine production after two to three years. Similarly, the few horizontal holes (three to four meters long) available for long-term monitoring show an initial brine production that rapidly decreased with time. Horizontal holes older than 2.5 years are not producing brine (Deal and others, 1989).

Brine recovery from downholes differ substantially from holes drilled in other orientations. Downholes tend to produce brine over extended periods of time and sometimes show increased seepage rates (Deal and others, 1989). Closely spaced holes (less than two meters apart) may have seepage rates, volumes, and brine levels varying by two orders of magnitude or more.

Small encrustations of halite occur on the ribs of many underground excavations. The halite encrustations were first noticed in 1982 shortly after excavations began at the WIPP (TSC-D'Appolonia, 1983a and 1983b; Alcorn, 1983). They are usually small (1-2cm), isolated buttons of halite whose outer layers are commonly crystalline. The encrustations often coalesce forming larger accumulations in areas of greater seepage, particularly above and below the Orange Marker Band where clay layers occur. The encrustations are caused by brine seeping very slowly out of the ribs and evaporating on the exposed surface. If flow is greater, then sheet deposits develop that rarely exceed more than 1-3 mm in thickness over a very limited area (fractions of a m^2). Weeps occur commonly on vertical surfaces (ribs/walls) but rarely develop on the back (roof) of the excavations. This strongly suggests the brine causing the weeps flows horizontally along bedding with little cross-flow, at least until open fractures develop which permit the brine to drain downward.

Weeps can form very quickly after mining in the underground. Brine weeps have been observed along the face shortly after mining while gases bubble through it from the rock beyond the face (Deal and Case, 1987). As the excavations age, however, development of the weeps slows and ceases.

Weep encrustations were collected from three vertical surfaces, each about 7.4 m^2 (80 ft^2) in area. The time since the initial excavation of the vertical surface was 502, 520, and 1211 days. The average seepage rate necessary to form the encrustations was calculated to be 0.57, 0.13, and 0.13 $l/m^2/yr$, respectively (Deal and others, 1989).

One year from the initial sampling at these locations, only very small amounts of encrustations had reestablished themselves. This is documented in previous observations (Deal and Case, 1987; Deal and others, 1987) and substantiates the conclusion that encrustation growth is arrested a few years after initial excavation (Deal and others, 1989).

Characterization of Brine Geochemistry

Geochemical analyses of the brine has proven to be an extremely useful tool in understanding the modes of brine occurrence in the Salado Formation and the means by which it enters the excavations. Many of the difficulties regarding analysis of water with high salt content have been overcome (Deal and others, 1987; Deal and others, 1989). Analysis of many downhole brines indicates that much of the brine is not indigenous to the Salado Formation. It was introduced during the course of mining operations for purposes of dust control and roadbed consolidation. In the Panel 1 area, water was spread to consolidate the floors. Mixing models for these brines indicate approximately 40 percent of the brine recovered from a downhole penetrating Marker Bed 139 may have originated from this construction practice (Deal and others, 1989).

Brines recovered from upholes have been modified by evaporation during the sample collection process. Anomalous compositions of brines recovered from upholes can be accounted for by evaporation due to the slow accumulation of the brine. Variations in brine composition recovered from downholes suggests spatial heterogeneity exists. This implies mixing and fluid homogenization is limited within the Salado Formation at the WIPP repository horizon. The heterogeneity of downhole brines cannot be linked to larger-scale vertical migration of waters from the overlying Rustler Formation or underlying Castile Formation, because each of these formation waters are chemically distinct from WIPP brines (Deal and others, 1989; Abitz and others, 1990).

Major-element compositions (Stein and Krumhansl, 1986; Deal and others, 1989; Abitz and others, 1990) of the WIPP brines suggest an origin from evaporating seawater that had precipitated halite, modified by diagenetic reactions with gypsum, magnesite, and polyhalite; and by ion-exchange with clay minerals. A high magnesium and bromine content argue strongly that these brines originated as residual fluids, not as infiltrating groundwater that subsequently dissolved salt. The major-element compositions of brines recovered from downholes are distinct from fluid inclusions in WIPP halite (Stein and Krumhansl, 1986, 1988), suggesting no mixing and implying little movement of the brines. This observation also indicates the brine recovered in drillholes is largely intergranular fluid, and not intragranular fluid released by migration of fluid inclusions to grain boundaries by stress relief.

Rock-brine equilibria were evaluated using the brine analyses and the speciation-solubility code EQ3NR (Wolery, 1983). Modeling indicated all WIPP brines are saturated with respect to anhydrite, barite, fluorite, glauberite, gypsum, and halite. Several brines were calculated to be saturated with respect to celestite, dolomite, magnesite, and polyhalite (Deal and others, 1989; Abitz and others, 1990). Model results agree with the observed mineralogy at the WIPP repository and support the contention that WIPP brines are intergranular fluids which have equilibrated with evaporite salts.

Finally, the analytical results and solubility calculations (Deal and others, 1989; Abitz and others, 1990) argue for derivation of WIPP brines from near-field, intergranular fluids. Although the data does not unequivocally rule out large-scale brine migration, the time scale required for fluid migration through the Salado halite would have to be greater than that required for diagenetic reactions which produced magnesite, polyhalite, and quartz. Excluding human intrusion scenarios, time constraints on fluid migration through halite due to the present hydrologic system after the repository is sealed and repressurized suggest that soluble radionuclides will be restricted to the near-field environment of the waste for time periods sufficient to meet regulatory guidelines.

Bacteriological Studies

Studies were conducted to characterize the presence of bacteria in the WIPP underground. Cultures were prepared from brines in the facility, muck on the facility floor, and Salado cores. Bacterial growth could not be seen in cultures from the Salado cores, but a total of 48 different bacterial forms were identified in cultures from the brine and muck samples. The bacteria cultured were either halophilic or halotolerant and were presumably introduced during the mining activities. Many of the forms cultured are similar to forms in the surficial salt ponds near the WIPP. No bacterial forms were found that constitute a health hazard to the workers in the facility (Deal and others, 1989).

Characterization of the Moisture Content of the Salado Formation

Determination of the moisture content of the map units exposed in the workings was initiated in 1987 (Deal and others, 1987) and completed in 1988 (Deal and others, 1989). Moisture content is defined as the weight percent of water lost by a sample when heated to 95°C. A total of 11 different stratigraphic horizons were sampled in the underground. Samples taken throughout the facility represented varying times since excavation. The water quantified in this manner should be a reasonable measure of moisture present in the salt that is available to move into the excavations under local pressure gradients. Only a fraction of the available brine will actually seep into the excavations. No clearly discernible temporal or lateral trends in moisture content were found. Moisture content did vary with stratigraphy and was correlated directly with clay content.

Moisture content varied from 0.01 percent by weight for clear halite to 6.67 percent weight for an isolated sample selected for high clay content. Analysis of 545 samples gave an average near-field moisture content of 0.5 to 0.75 percent by weight. This is a reasonable representative value of the moisture present in the repository host rock. The average moisture content for all 545 samples was 0.55 percent by weight. However, the weighted average moisture content for units exposed at the repository level, which takes the stratigraphic thicknesses of Map Units 0 through 4 into account, is approximately 0.60 percent by weight (1.56 percent by volume) (Deal and others, 1989).

Direct Examination of Drillholes Using a Video Camera

The examination of boreholes using a video camera was begun in 1987 (Deal and others, 1987) and completed in 1988 (Deal and others, 1989). The examination was unsuccessful in delineating wet zones and zones of potential inflow in the boreholes. The high reflectance of the salt crystals and zones of wetness could not be differentiated with the available equipment. Thin clay seams were observed that appeared to be prevalent in the upholes. In many cases, clay was observed being squeezed into the drillholes.

Conductivity Measurements

Work in 1988 and 1989 demonstrated slim-hole conductivity equipment used in air-filled drillholes can provide useful data. A program of geophysical logging of upholes and downholes in the northern, experimental end of the facility was undertaken. The purpose of the program was to characterize the moisture content of the stratigraphic units in areas far from the working face, floor, or back. The induction logging tool that was used has a maximum response to the portion of the formation that is about 0.5 meters away from the borehole. The tool reacts much more strongly to brine that is intergranular and occupying interconnected spaces than to intracrystalline fluid inclusions. For clear halite units, moisture content calculated from the logs agree with the measured moisture content of samples taken at the face.

Borehole induction logging proved to be a reasonably efficient and accurate method of measuring conductivity of the rock units and, thereby, their moisture content. The moisture content measured by laboratory analysis and those calculated from the geophysical logs show an absolute difference of 0.05 percent when the averages of all units are considered. This is a good correlation, given the spatial differences in the sampling sets. Induction log calculations indicate anhydrites and anhydritic units to be substantially wetter, and argillaceous halite units to be drier than the samples of the same units taken at the face (Deal and others, 1989).

OCCURRENCE OF BRINE AND NITROGEN IN BEDDED SALT

The complex evaporite sequence exposed in the WIPP excavations was initially deposited in a part of the Permian sea where normal marine waters were concentrated by evaporation. The Salado Formation is composed predominantly of halite. Rainfall, fresh water and clastic input from nearby exposed land areas, and influxes of normal marine water into the evaporitic basin has caused the resultant rock to be fairly complex, containing some clay and other evaporite minerals such as polyhalite, anhydrite, and various potash minerals (Holt and Powers, 1984; Holt and Powers, 1988; Holt and Powers, 1990). Some residual seawater containing dissolved gases derived from the Permian atmosphere was trapped in the precipitating evaporites. The geochemical data from the downholes in areas where construction water has not been spread show ionic ratios similar to seawater that has precipitated halite (Abitz and others, 1989; Deal and others, 1989; and Abitz and others, 1990). This supports the contention that these ancient fluids may be a major component of the brine found seeping into the WIPP excavations.

After burial beneath the sea floor, a chemically and physically complex set of diagenetic processes acted on the deposits, causing extensive recrystallization to occur. The composition of the residual brine and gases in the salt was also changed during diagenesis, and it is likely residual oxygen combined with other elements at that time. It is noted that the WIPP brines essentially contain no dissolved oxygen or carbon dioxide. Gas exsolving from the brine is mostly nitrogen with traces of methane. The nitrogen may either exist within the rock matrix as free gas or be dissolved in the brine. The amount of nitrogen dissolved in the brine depends on the pressure and temperature of the undisturbed salt. Exsolving gas drives brine to the surface of the excavations (Deal and Case, 1987).

Water within the Salado Formation is present in several ways (Deal and Case, 1987): 1) in hydrous minerals such as gypsum and clays, 2) as fluid inclusions in halite and other crystals, and 3) in intergranular pores and open fractures. Deal and others (1989), pointed out that intergranular moisture is associated with underconsolidated clays, in salt crystals as well as between halite, anhydrite, and other crystals. The concept of undercompacted clays is discussed further in the following section.

DEVELOPMENT OF THE DEFORMATIONAL ENVIRONMENT

Studies during the BSEP (Deal and Case, 1987; Deal and others, 1987; and Deal and others, 1989) were directed toward the environment in and directly adjacent to the underground excavations. These studies and others (Bechtel National, Inc., 1986; Borns and Stormont, 1988; Francke and others, 1989; Francke and others, 1990) show the rock immediately surrounding the excavation is altered significantly by deformation induced by the rock excavation. The common theme of the BSEP investigations is 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, sometimes described as the Disturbed Rock Zone, is discussed in most basic references on rock mechanics (e.g., Brady and Brown, 1985; Coates, 1981; Goodman, 1980). More specific discussions of the development of the Disturbed Rock Zone in evaporite beds is provided by Baar (1977), Mraz (1980), and Kelso and others (1982). Borns and Stormont (1988) specifically address the Disturbed Rock Zone developing around the excavations at the WIPP.

Previous discussions do not make it adequately clear that there are generally two parts to the deformational envelope around underground excavations in salt: 1) an outer zone where dilatancy and microfracturing occur with pore pressures above atmospheric, and 2) an inner zone characterized by macrofracturing and pore spaces where the pressures are essentially at atmospheric. Plastic materials behave somewhat differently than elastic solids; plastic deformation does not produce dilatancy. 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" (Mraz, 1980). Brine moving toward the excavation behaves differently in these two zones. It is important to consider both of them when discussing brine seepages into the WIPP excavations.

Because of the ambiguities of the terms Damaged Rock Zone and Disturbed Rock Zone, the following terminology is proposed. Damaged Rock Zone is restricted to the areas of intense macrofracturing directly surrounding the openings where pore pressures are essentially atmospheric. Disturbed Rock Zone is the entire volume of rock whose porosity and permeability has been affected by the excavation as determined by measurements of the porosity and permeability, and includes both the Damaged Rock Zone and the deeper zone of dilatancy and plastic deformation.

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.

Excavation geometry around the openings at the WIPP is modified. It includes failure of roof and floors due to heaving, separation along clay seams, and the development of macrofractures in ribs (Bechtel National, Inc., 1986; Francke and others, 1990).

Because of the differences in ductility between salt and anhydrite, the brittle anhydrite becomes preferentially loaded as the salt deforms adjacent to it. Beneath the excavations, the approximately one-meter thick anhydrite Marker Bed 139 acts like an end-loaded beam. This results in a stress concentration in the vicinity of the anhydrite. The dish-shaped fractures are distorted, they tend to flatten near the room center and concentrate within the body of the anhydrite (Bechtel National, Inc., 1986). Two and one-half years after excavation, air-filled fractures up to 150 mm wide have been observed (Bechtel National, Inc. 1986). The largest separation documented is about 230 mm wide about five years after excavation (Francke and others, 1988). Some sub-horizontal fracturing has been noted just above clay E, which occurs at the base of the anhydrite, approximately two meters below the floor of the excavations, but no separations at clay E were noted (Bechtel National, Inc., 1986). This may be because the creeping salt was deforming upward, pushing against the anhydrite and keeping the clay confined.

Discontinuities, mostly thin clay partings and anhydrite beds, are found above the roof of the excavations. Separations along these discontinuities occur as the roof beam sags into the excavation, especially at clay G at the base of anhydrite "b", a thin anhydrite located about two meters above the roof of the typical waste storage room. Separations at clay G are typically a few millimeters wide two years after excavation, and in an extreme case (SPDV Test Room 1), approximately 100 mm six years after excavation (Francke and others, 1989; Geotechnical Data Files, WIPP site).

Mining sequence and stratigraphic variations are other factors affecting the details of fracture development. In the case of large-scale fracturing six years after mining, it seems unlikely that the effects of mining sequence would be as important as it would be only days after mining. It seems likely, however, when applying the discussions in this section to an understanding of possible brine seepage pathways, that small local variations in stratigraphy or stress distribution resulting from sequential mining may be extremely important. In discussing the striking variation observed in seepage into closely-spaced holes, Deal and Case (1987) cautioned that "the great variation in inflow characteristics between locations only a short distance (a few meters, or in some instances, less than a meter) apart make the discussion of 'averages' or 'typical occurrences' difficult or misleading."

Deal and Case (1987) and Deal and others (1989) describe many of these occurrences in detail (especially the MIIT holes in Room J, the L1S holes in Room L1, and holes DH42 and DH42A in Room G). They also describe inflow variations that seem to be the result of stress redistribution caused by sequential mining (hole DH215) and the occurrence of macrofracturing (hole NG252). Abundant evidence exists that the specific response to stress around actual openings at the WIPP (both in terms of macrofracturing and brine seepage) can be quite complex in detail.

SOURCE AND MECHANISM OF MOVEMENT OF THE BRINE

The source and mechanism of release of the formation brine is still open to question. A major point of uncertainty is whether a significant amount of brine is moving through the undisturbed salt toward the repository. There are at least five possibilities:

1. Perhaps the simplest explanation entails the existence of a hydrologic system within interconnected porosity throughout the body of the Salado Formation. Although permeabilities are extremely low, on the order of 10^{-21} to 10^{-20} m^2 (one to ten nanodarcy) (Davies and Freeze, 1990), with perhaps higher permeabilities in anhydrite units and along discontinuities within the stratigraphic package, the pressure gradients between the recharge area and the formation and between the formation and the one atmosphere pressure of the drifts may be sufficient to drive brine into the workings. This scenario is attractive because it is relatively easy to model using existing concepts and tools. Furthermore, if permeabilities are known, long-term inflow estimations can be made with considerable confidence.
2. Near-field deformation (the development of the Disturbed Rock Zone) may modify brine flowing toward the excavations from the far field (beyond the Disturbed Rock Zone). Based upon the currently accepted rheologic models, porosity in the salt increases due to the elastic response associated with the convergence of the walls, floors, backs, and ribs. The increase in porosity should also result in an increase in permeability in a coupled relationship, although the exact relationship between porosity and permeability is not well-established. Nevertheless, the increase in porosity and permeability offers the opportunity for any free brine available in the immediate vicinity of the workings to migrate toward the workings through greatly enhanced pathways. In this manner, the coupled relationship between deformation, porosity, permeability, and available brine can modify brine flow paths close to the excavations. Preliminary modeling suggests that the pore spaces in the zone of dilatancy will increase faster than brine can flow in from the far field, and that the zone around the excavation will support multi-phase flow which may include brine, gas exsolving from the brine, and air from the excavation (Deal and others, 1989).
3. Another possibility is immobile brine in the undisturbed, far-field salt. Flow through the salt toward the repository only occurs in response to deviatoric stresses resulting from the excavation of the repository. This possibility was suggested by Deal and Case (1987), although they pointed out that flow through interbeds and along other planar discontinuities could be much greater. This possibility has been difficult to test, as direct measurements of the undisturbed salt is exceedingly difficult to accomplish without altering the very parameters that are being measured. If this condition actually occurs, considerable difficulties are introduced into any attempts to model brine flow to the excavations. Preliminary hydraulic testing at the WIPP repository level (-655 m) has found that the hydraulic conductivity, if it exists at all, of relatively pure halite is immeasurably low; argillaceous halite ranges from about 4×10^{-9} to 7×10^{-8} ft/day; and anhydrite Marker Bed 139 *ranges from* 1×10^{-7} to 2×10^{-6} ft/day (Beauheim and Holt, 1990).
4. From the hydraulic conductivity data cited above, it is clear that some Anhydrite beds (and possibly other interbeds, bedding planes, and stratigraphic partings) can provide preferential flow paths for the brine. It seems reasonable that preferential flow along interbeds

probably does occur, modifying all of the above hypostheses.

5. If the clays present in the Salado Formation are underconsolidated, then they may provide a local source of brine. Deposition of clays was followed by deposition of impermeable evaporite lithologies, which inhibited the transport of fluids. In more conventional clastic depositional systems consisting of sandstones, siltstones, and shales, fluid loss from the clays normally would be expected to occur as a result of compaction. Because the impermeable evaporites formed early in the sequence (Holt and Powers, 1990), opportunities for fluid loss as a result of increasing lithostatic pressures were limited until the excavations were constructed. Deformation due to excavation closure created new permeability and allowed the underconsolidated materials to lose some of their water. This hypothesis assumes lithostatic loading in the pillars between the excavated rooms drives moisture out of the clays, along generally horizontal flow paths, to the excavations. The moisture content data clearly indicate that argillaceous units have a higher water content (Deal and others, 1989).

The condition that is uniquely different when considering the hydrology of the salt beds at repository depths is that the bulk of the material is a plastic, and the seeping brine involves small volumes moving at very slow rates. Usual hydrologic problems consider rocks as elastic solids, where the rock matrix supports the weight of the overburden and the fluid pressures in the contained pore spaces are generally at hydrostatic pressures. Additionally, it is normally assumed that the physical characteristics of the rock, such as porosity and intrinsic permeability, are constant during the time under consideration. This last assumption clearly does not hold in the disturbed zone close to the WIPP excavations.

The plastic nature of the salt raises another question. What conditions are necessary to keep a cavity open in a plastic material? It seems necessary to have the cavity filled with something--liquid or gas--under the same pressure that confines the plastic material. Fluid pressure in the pore spaces probably prevents additional plastic closure of those pore spaces prior to disturbance of the salt.

As the salt creeps into an excavation, the porosity and permeability of the salt near the excavation initially increase. If the salt has any intrinsic permeability, it is likely that the brine and gas will move through openings in the salt more rapidly than the salt can deform. It is therefore possible that at some distance from the excavation, where a small pressure gradient toward the excavation exists, brine and gas will flow through the pore spaces reducing the pressure within them, allowing salt-creep closure under gravity-induced lithostatic loading to reduce the size of the conduits (microfractures, intergranular spaces, pores, or the apertures that connect them). This process might continue until the open pathways become so small that Darcy's Law no longer applies, surface-tension dominates and, for all practical purposes, the fluids become immobile and intrinsic permeability is reduced to zero. If this is possible, then the brine seepage phenomena may be self-limiting and, at least in a horizontal direction away from the excavations, a "barrier" zone of reduced or negligible permeability might naturally develop.

The moisture content sampling of the ribs and cores taken from the repository horizon established that the free brine content varies between approximately three to four weight percent for the wetter lithologies to as little as 0.1 weight percent free water for a pure halite lithology. The overall average of all lithologies is approximately 0.6 weight percent. The extensive sampling has established that free brine is available in the stratigraphic horizons adjacent to the excavations. The permeability enhancement associated with the deformation should make the brine more mobile in response to the pressure gradients and simple gravity flow.

EVOLUTION OF THE HYDROLOGIC SYSTEM

Our present feeling is that most of the brine flows in a local system developed within the disturbed zone, induced by mining of the excavations at the WIPP. Brine flow almost certainly occurs preferentially along more conductive interbeds and stratigraphic discontinuities. Some of the brine may be squeezed out of clays by compaction in the pillars. We cannot unequivocally rule out the possibility of some contribution from the far field, but if there is some, we feel that it is probably small. We feel that after several years, as the outward extension of the disturbed rock zone slows, brine movement to the repository excavations should decrease and that there is a good possibility that it might become negligible. We have learned much about the brine occurrences at WIPP, but extensive investigations of the brine phenomenon continue in an effort to resolve the remaining uncertainties.

Because salt is plastic, fluid pressure in the undisturbed salt is probably equivalent to the undisturbed normal stresses acting on the rock. When rock stresses are relieved by excavation, deviatoric stress cause the salt, brine, and gas to move toward the excavation. As fluid pressure decreases, dissolved nitrogen is released from the brine and becomes free gas, partially offsetting the fluid pressure drop. Gas and brine move along sub-horizontal flow paths to the vertical surfaces of the excavations, where brine weeps and salt encrustations develop.

As creep closure of the excavations continue and the disturbed rock zone develops, the deformation within ribs, backs, and floors appears to differ somewhat. In all cases, however, the formation of a fracture system capable of channeling brine into the porosity developing within the floor is a key factor in the distribution of brine within the repository. As the halo of fracturing matures it would be expected that near-surface weeps should be cut off from their sources and cease to be active areas of evaporation and brine accumulation.

Brine previously delivered to the surfaces of the excavations is probably still being delivered, though at slower rates, to the lower pressure areas of the excavation, probably represented by the fracture systems. The fractures provide a plumbing system to conduct the brine to the floors and the sump consisting of the fractured salt and Marker Bed 139.

The path of brine from the deforming areas of the back is probably more circuitous. Some brine probably continues to be delivered to boreholes that extend upward from the back with some being delivered to the fracture system. The flow paths will have to cross clay interbeds, that may tend to retard or divert flow. The fracturing close to the excavations tends to be dish-shaped, channeling brine away from the center of the excavation, or subparallel to the clay interbeds. As a result, seeps from holes drilled upwards from the facility horizon typically continue to produce brine much longer and more prolifically than holes drilled horizontally into the ribs. Brine accumulations trapped by clay seams are occasionally encountered when drilling upholes in older parts of the facility.

In contrast, holes drilled downwards into Marker Bed 139 and lower horizons usually continue to produce brine even in the oldest parts of the facility. The geochemistry data clearly indicate, however, that much of the brine acquired from the downholes is contaminated by non-formation brines, especially in those areas of the workings where construction water is commonly spread, and therefore the total amounts of the brine recovered must be discounted by an appropriate amount.

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