

SANDIA REPORT

SAND87-1375 • UC-70

Unlimited Release

Printed September 1988

An Interim Report on Excavation Effect Studies at the Waste Isolation Pilot Plant: The Delineation of the Disturbed Rock Zone

David J. Borns, John C. Stormont

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550
for the United States Department of Energy
under Contract DE-AC04-76DP00789

***When printing a copy of any digitized SAND
Report, you are required to update the
markings to current standards.***

Issued by Sandia National Laboratories, operated for the United States Department of Energy by Sandia Corporation.

NOTICE: This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government, any agency thereof or any of their contractors or subcontractors. The views and opinions expressed herein do not necessarily state or reflect those of the United States Government, any agency thereof or any of their contractors.

Printed in the United States of America
Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

NTIS price codes
Printed copy: A03
Microfiche copy: A01

**AN INTERIM REPORT ON EXCAVATION EFFECT STUDIES
AT THE WASTE ISOLATION PILOT PLANT:
THE DELINEATION OF THE DISTURBED ROCK ZONE**

David J. Borns

Division 6331

and

John C. Stormont

Division 6332

Sandia National Laboratories

Albuquerque, NM 87185

ABSTRACT

For nuclear waste repositories with both long operational periods (50 yr) and long performance assessment periods (10 000 yr), the Disturbed Rock Zone (the zone of rock in which the mechanical and hydrologic properties have changed in response to excavation; abbreviated as DRZ) is important to both operational (e.g., slab or fracture failure of the excavation) and long term performance (e.g., seal system performance and fluid transport). At the Waste Isolation Pilot Plant (WIPP), the DRZ has been characterized with three approaches: visual observation; geophysical methods; and permeability measurements. Visual observations in drillholes indicate that fluids and fractures are common in the host rock of the underground facility. Geophysical studies have utilized radar, electromagnetic (EM), and direct current (DC) electromagnetic methods. Radar has been useful, but the penetration is limited by the water content and bedded nature of the host rock. The EM method was able to detect a fourfold increase in resistivity from 1 to 5 m into the rock. This trend reflects a fourfold increase in the moisture content from near the excavation (0.5 to 1% by weight) to 5 m into the host rock (2 to 3% by weight). The DC method has been able to detect zones of moisture around the excavation. Numerous gas permeability measurements indicate that beyond 2 m from an excavation halite and interbeds (anhydrite and clay) allow very low gas flow (calculated permeabilities < 1 microdarcy for gas flow tests and < 0.01 microdarcy for brine-based permeability tests). Within 2 m of the excavation, very high flow rates (10^4 SCCM) were measured. All three approaches have defined a DRZ at the WIPP extending laterally throughout the excavation and varying in depth from 1 to 5 m, according to the size and age of the opening.

Table of Contents

INTRODUCTION	1
VISUAL OBSERVATIONS IN BOREHOLES	3
Chronology of Fracture Observations	3
GEOPHYSICAL OBSERVATIONS	6
In-Mine Electromagnetic Surveys	6
Borehole Moisture and Density Measurements	7
In-Mine Radar Surveys	9
HYDRAULIC TESTING	12
Brine Inflow	12
Gas-Flow Testing	12
Tracer Gas Studies	15
DISCUSSION	17
Possible Mechanical Processes Active in the DRZ	17
Hydraulic Characteristics of the DRZ	17
Implications of the DRZ:	18
On Previous Findings	18
On Observed Closure	18
On Room Stability	19
On Seal Design	19
On Performance Assessment	19
SUMMARY	21
Effects of the DRZ on Rock Properties and Behavior	21
Character of the Disturbed Rock Zone	21
Effects of the Age and Size of the Excavation	21
REFERENCES	23

Figures

1. Underground Wipp Facility	2
2. Key Stratigraphic Units at WIPP Facility Level	5
3. Observed Fracture Pattern for 4 x 11 m Room	6
4. Location of EM-31 and EM-34 Traverses (in Black)	8
5. Apparent Resistivity versus Water Content	10
6. Apparent Resistivity Measurements in Ohm-Meters	11
7. Gas Flow Rates in Halite Test Intervals	13
8. Flow Rates in Interbed Layers within 2 m of Drifts	13
9. Width of Drift versus Flow Rate in MB139	14
10. Contours of Gas Flow Rate around N1100 Drift at 4 yr	14
11. Fracture Pattern around an Excavation in Salt	22

Table

1. Normalized Flow Rates (SCCM)	15
---	----

INTRODUCTION

Following excavation of underground openings, a Disturbed Rock Zone (DRZ) forms in the wall rock and is defined as the zone of rock in which mechanical properties (e.g., elastic modulus) and hydrologic properties (e.g., permeability and fluid inflow) have changed in response to the excavation. The present extent of the DRZ around workings at the Waste Isolation Pilot Plant (WIPP) is delineated in this paper based on the measurement of rock properties in field studies. The measurement of these rock properties is relatively straightforward, but the processes involved in the development of a DRZ are complex, although basically related to stress relief and/or rapid strain rates. The formation of the DRZ drives coupled processes such as changes in permeability in response to fracture growth. This report will delineate the DRZ in the underground facility at the the WIPP based on field observations and the available measurements of rock properties and will provide a basis for further studies of the processes that result in the development of a DRZ. Since nuclear waste repositories have both long periods of operation (50 yr) and performance assessment (10 000 yr), characterization and understanding of the DRZ are important to the evaluation of operational (e.g., slab or fracture failure of the excavation) and long term performance (e.g., seal system performance and fluid transport).

The WIPP is an underground research and development facility currently under construction in bedded salt near Carlsbad, New Mexico. The purpose of the WIPP is to demonstrate the safe storage of transuranic wastes generated by defense activities of the United States. The waste disposal technology developed has applications to other programs, in the U. S. and elsewhere, which are considering underground disposal of nuclear wastes in salt.

The WIPP underground facility lies 653 m below the surface (Figures 1 and 2). The underground areas are divided basically between three tasks: site and preliminary design validation (SPDV); technology experiments; and demonstration of full-scale TRU waste disposal. Mining of the SPDV areas started in 1982, of the experiment areas in 1984, and of the waste disposal panels in 1986.

At the WIPP, the DRZ has been characterized using three approaches: visual observation; geophysical methods; and measurement of hydraulic properties. All three approaches have defined a DRZ at the WIPP extending laterally throughout the excavation and varying in depth from 1 to 5 m, according to the size and age of the opening. This report contains some initial results of an ongoing experimental program to develop a more detailed three-dimensional definition of the DRZ.

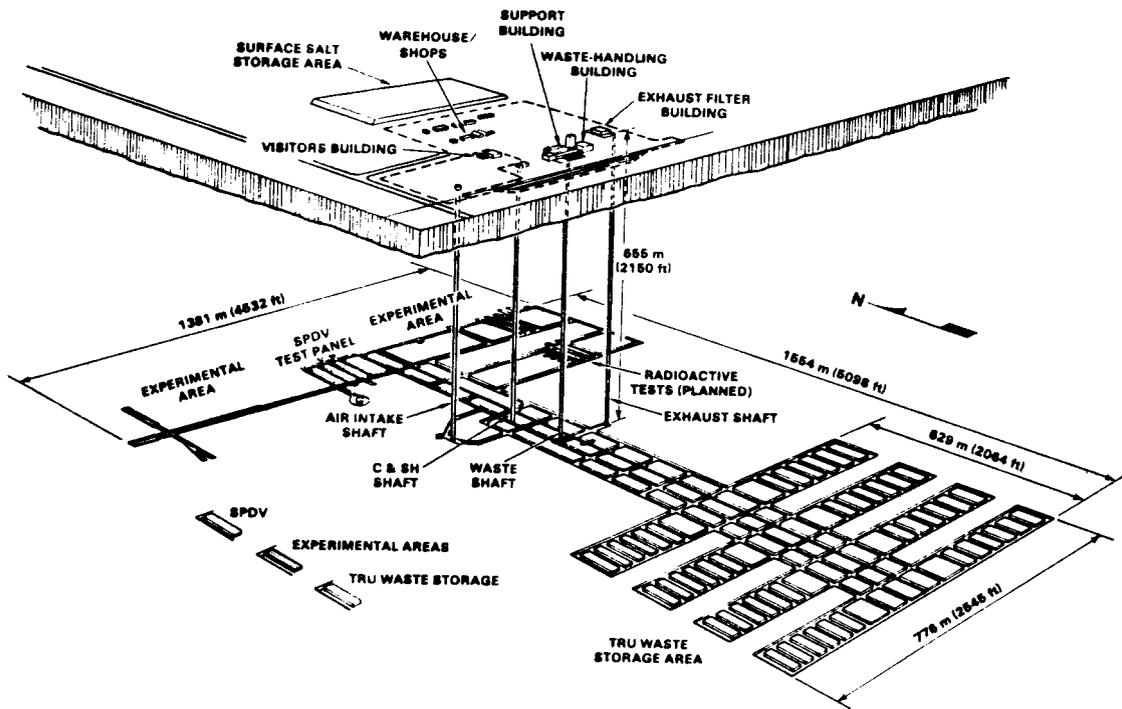


Figure 1. Underground WIPP Facility

VISUAL OBSERVATIONS IN BOREHOLES

During development of the underground workings at the WIPP site, numerous drillholes were made for stratigraphic studies, test areas for experiments, and construction foundations. As the presence of a DRZ became apparent, Bechtel National (1986) drilled numerous holes specifically to investigate the DRZ. Therefore, we have a data base of direct observations of the DRZ spread both spatially and in time. These visual observations using drillholes indicate that fractures (*with apertures greater than 2 mm and visible without enhancement to the naked eye*) and fluids are common in the wall rock of the underground facility. The observations from these boreholes suggest the development of an elliptical pattern of fractures around an excavation as summarized in an idealized cross-section of a WIPP Room (Figure 3). The basic features of these observations are as follows:

- An arcuate fracture system, concave towards the opening, develops in the floor and the back, crosscutting the stratigraphy.
- Separations may develop along stratigraphic markers such as clay seams.
- Shear displacements are observed along some fractures and separations.
- Vertical fractures and spalling are observed within the ribs.

A reexamination of existing boreholes was conducted in 1987 (Francke, 1987). This reexamination showed that the extent of observed fracturing in borehole arrays increased from 48% of the array locations in 1986 to 73% in 1987. The locations without fractures are largely restricted to drifts with

narrow spans (4 x 4 m). In the oldest 11 x 4 m test rooms (Room 1 through 4), 100% of the locations exhibited fractures 2 mm or greater.

Chronology of Fracture Observations

- In 1983, the exploratory drift, E140 (also known as the south drift), was driven 1000 m south of the site center to verify the stratigraphic continuity and suitability of the facility horizon in the waste panel area. After completion of this drift, a separation was observed consistently 10-15 cm up into the back. This separation was within a massive halite unit and was not associated with a clay seam. The separation appears to be related to a marked change in halite grain size. In portions of the south drift, the rock salt below this separation has been scaled down and/or rockbolted
- In the autumn of 1984, the structures of Marker Bed 139 (MB139) were studied in several drillholes in the north end of Room 4 (Borns, 1985). MB139 was found to be fractured. Many of these fractures were interpreted to have existed prior to excavation, and these fractures also provided zones of weakness that reopened in response to the excavation. At the same time, several 0.9 m-diameter drillholes were completed in the south end of Room 4. In these holes, fractures developed in the halite above MB139 and within the marker bed.
- In the summer and autumn of 1985, a series of 22 0.9-m-diameter drillholes was drilled in the south end of Room 3 to provide the foundations for bulkheads (Room 3 has been divided in two with the south end becoming Room T).

These drillholes exposed fractures both in MB139 and in the halite above, as seen the year before in Room 4. However, due to the large number of holes drilled, the fracture system in Room 3 was much more exposed than in Room 4. All of the holes in Room 3 were interconnected by the fracture system. Exploratory drilling in the north end of Room 3 revealed that the fracture system extended throughout the room.

- In 1986 after the fracture systems in several of the SPDV rooms were documented, Bechtel National (1986), in order to gather more information for design validation completed a reconnaissance drilling project throughout the underground facility. This study found areas of fracturing outside the SPDV rooms, notably the shaft stations, and at

both levels of the facility horizon (Figure 2). A year later Francke (1987) reexamined the Bechtel drillholes and found that the extent of fracturing had increased significantly over a 1 yr interval.

- In 1987, Sandia National Laboratories (SNL) began to evaluate whether the back in test rooms could support hoist equipment. In this study, areally extensive separations were found in both rooms, and the rooms were rockbolted for protection. The mining contractor began to develop the working concept that similar fractures and separations would develop throughout the facility with time. An Openings Maintenance Program was started to set the criteria and methods for control of these fractures and related features.

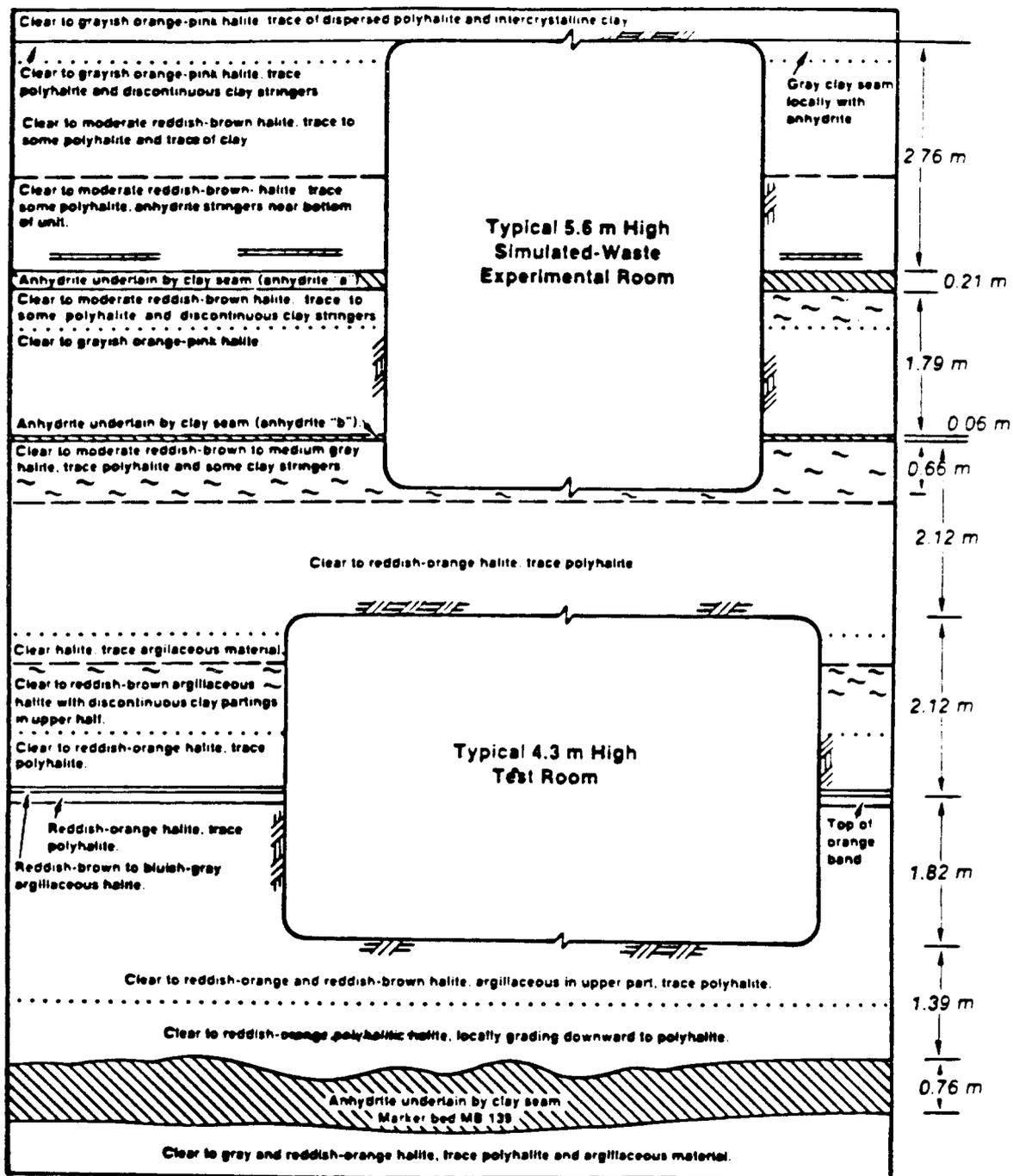


Figure 2. Key Stratigraphic Units at WIPP Facility Level

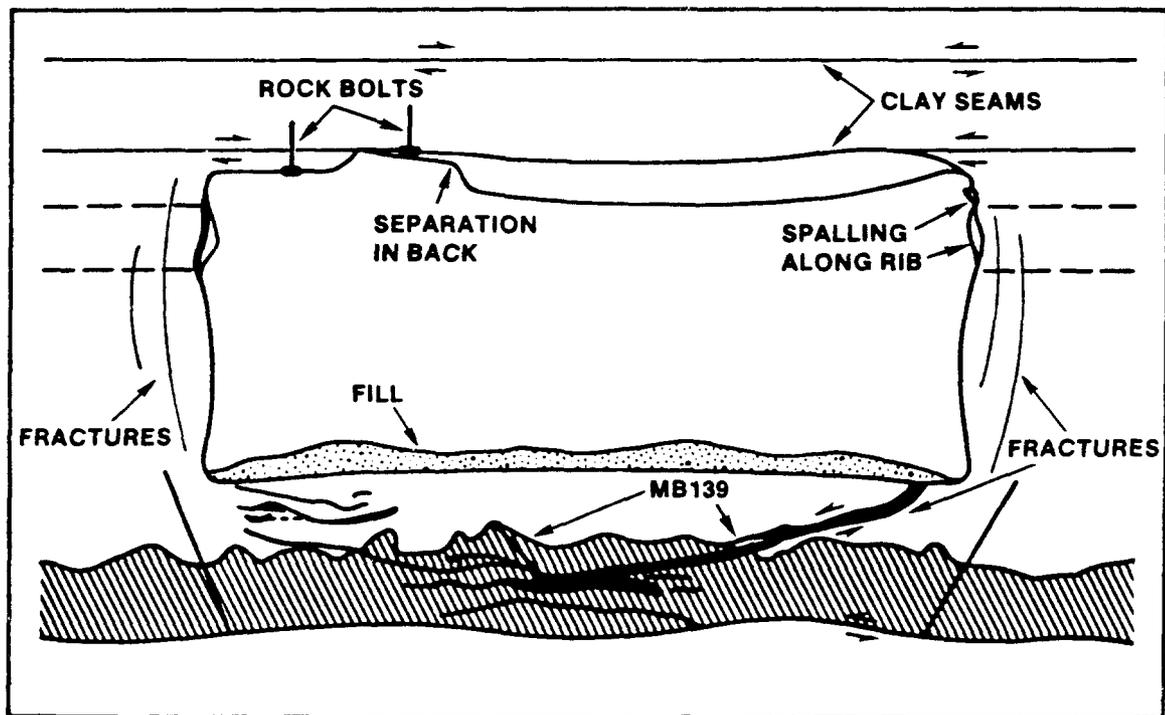


Figure 3. Observed Fracture Pattern for 4 x 11 m Room

GEOPHYSICAL OBSERVATIONS

In-Mine Electromagnetic Surveys

Electromagnetic methods measure the apparent resistivity of the host rock. Properties, such as permeability and fluid content, can be inferred or calculated from the resistivities. The initial phase of this study was the measurement of the electrical conductivity of the wall rock, using conventional electromagnetic coupling equipment. Two systems were used: the EM-31 and EM-34 systems manufactured by Geonics, Ltd., of Toronto, Canada (Keller et al., 1987; Pfeifer, 1987). In both of these the mutual coupling between two induction coils is measured and converted to apparent resistivity. With the EM-31 system, the two coils are separated by a distance of 3 m along the excavation surface. In the EM-34 system, the two induction coils are separated by 20 m. These configurations result in a distance of search (penetration) of 1 to 2 m (for the EM-

31) and 10 to 20 m (for the EM-34). Measurements were made at 3.2 m (EM-31) and 7.2 m (EM-34) intervals along the same traverses in selected drifts at the WIPP (Figure 4). In essence, this survey configuration measures the electrical conductivity (or resistivity--the reciprocal of conductivity) adjacent (EM-31) to the mined opening and 10 m (EM-34) away from the opening.

For the EM-31 system, the measured conductivities for the wall rock up to 2 m from the excavation range from 1 to 5 millisiemens per meter (from 200 to 1000 ohm-meters). For the EM-34 system, the deeper conductivity measurements, up to 20 m from the excavation, range from 7 to 10 millisiemens (100 to 140 ohm-meters).

The deeper measurements with the EM-34 show a conductivity several times larger than those measured with the EM31 system. The EM-31 and EM34 measurements are being compared with resistivities measured in salt mines in Germany by Kessels et al. (1985). Based on this comparison, we expect the free water content of the salt around the mine opening to increase from 0.5 to 1.0% (by weight) at the excavation surface to between 2.0 to 3.0% at several meters depth (Figure 5). This observation may reflect an alteration of the wall rocks of the tunnels due to drying by the ventilation system.

The second phase was the measurement of the electric field and electrical potential in the mine openings with a source of direct current sited on the surface. The rocks around the mine workings were energized using a fixed dipole source located on the Earth's surface. Two wells (located 1.0 km apart and with 300-m-deep casings) were used as electrodes. From the determination of the electric field at selected stations in the underground workings, apparent resistivities were calculated for the rock mass near the excavations.

The preliminary survey in the underground facility shows a broad range of lateral variation in resistivity (30 to 10 000 ohm-m, Figure 6). Some of this variation can be attributed to dehydration of the host salt adjacent to heated rooms and to zones where the wall rock is rich in brine and seen to visibly weep to the surface of the excavation. The sensitivity of this method is approximately proportional to the size of the conducting unit being detected (Pfeiffer, 1987). Roughly, a unit 1 m in length is detectable at a distance of 1 m and a body 30 m in length is detectable at a distance of 30 m. Future surveys using the DC method will be conducted with a shorter interval between

stations than the 100 m separation used in the experimental survey. The shorter separation will permit a determination of the size of the conducting units that cause the distinct variations in the apparent resistivities adjacent to the underground facility .

Borehole Moisture and Density Measurements

The U. S. Geological Survey (Hudson, 1987) conducted a series of trial moisture and density measurements in boreholes underground at the WIPP. These measurements are based on standard geophysical logging methods, such as neutron-epithermal neutron, neutron-gamma, and the Troxler-moisture meter. The specific probes for each method were calibrated using material mined from the WIPP to account for the effects specifically associated with the brine at the WIPP site, such as the high-chloride background. The moisture and density measurements were made in an array of drillholes (9 m deep) in the roof, back, and floor of a drift used in the gas-flow testing described below. The moisture content determined from these methods ranges from 3 to 5 weight % for the halite to as high as 9% in the anhydrite and clay marker beds above and below the excavations and within the DRZ. Although the application of these methods at the WIPP is still developmental and the calibration may require more examination, the halite moisture values from the logging probes are in the same range as the values determined by the TEM method described above. These moisture contents are 5 to 10 times larger than the moisture contents assumed earlier for WIPP salt (Powers et al., 1978). The moisture content of halitic interbeds cannot be attributed to accessory minerals: for example, polyhalite, which contains approximately 6% water by weight and comprises less

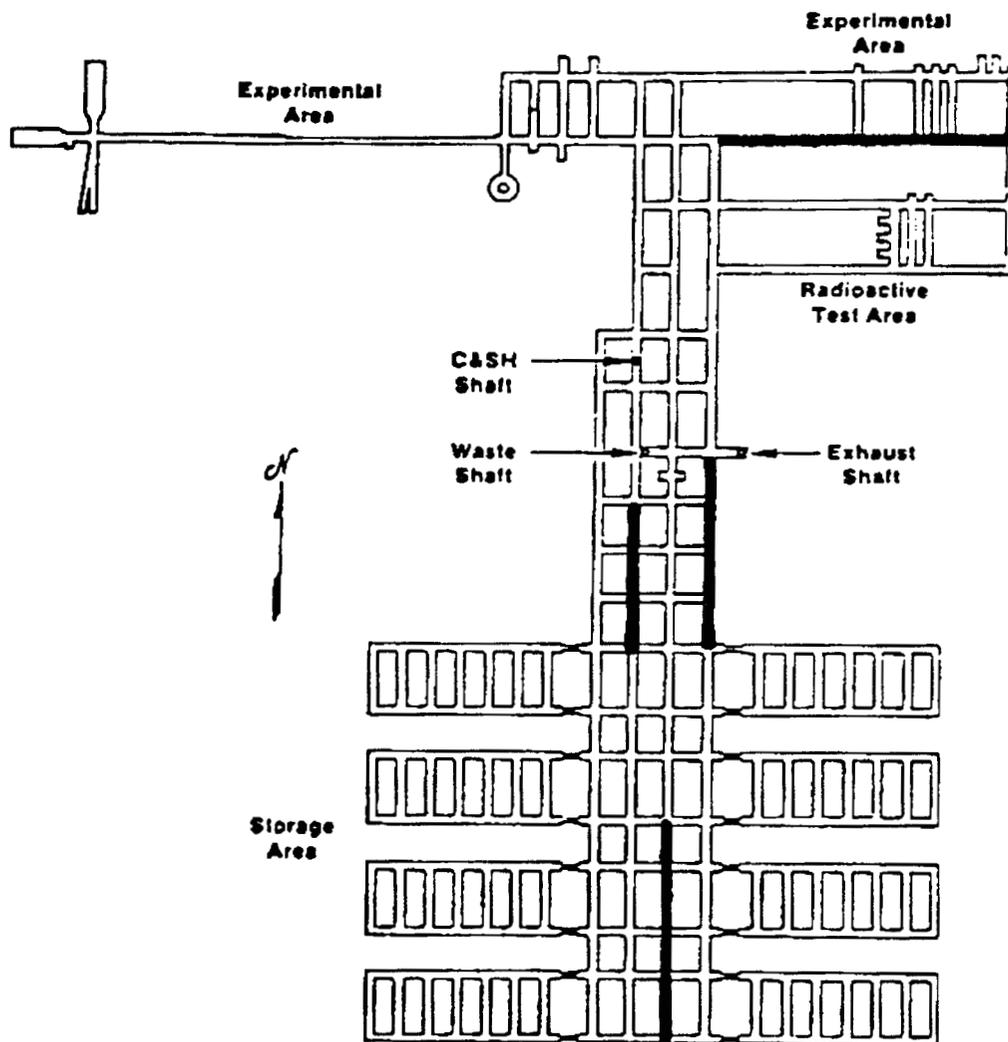


Figure 4. Location of EM-31 and EM-34 Traverses (in Black)

than 5% of rock salt, can only contribute 0.3% of the water present in the rock salt.

In-Mine Radar Surveys

Various radar methods have been considered as ways to map rock zones around underground openings in the WIPP project (Unterberger, 1981; Cook, 1982). It was thought that radar would be able to map discontinuities such as breccia pipes and detect brine and gas reservoirs as found in the salt deposits around the WIPP. These early radar studies were conducted, prior to underground construction at the WIPP, in the Mississippi Chemical Corporation Mine near the WIPP. While radar showed promise in dry, nearly pure halite, Unterberger and Cook in their separate studies found that radar was limited by presence of impurities such as water and clay in the halite from bedded and domal salt deposits. Unterberger found a high reflection coefficient for the air-rock interface in the in situ

mine tests of radar. He speculated that this high coefficient may be due to a higher water content for rock salt than expected. Reverberations were induced by the radar pulse within the rock salt at early times in Unterberger's experiment. These early time reverberations effectively obscured any returns from deeper into the rock mass .

Cook (1982) also found that radar was ineffective in bedded rock salt when probing for a breccia pipe underground. Cook noted that clay seams and other conductive inclusions in halite will limit the penetration of the radar system, decreasing its effectiveness as a survey method. Despite these limitations, the project has proceeded to field several surveys of the test rooms at WIPP. It has been suggested based on these surveys that radar can detect fractures in the 0 to 1 m range. The complete evaluation of the method will await the reports on this set of field surveys.

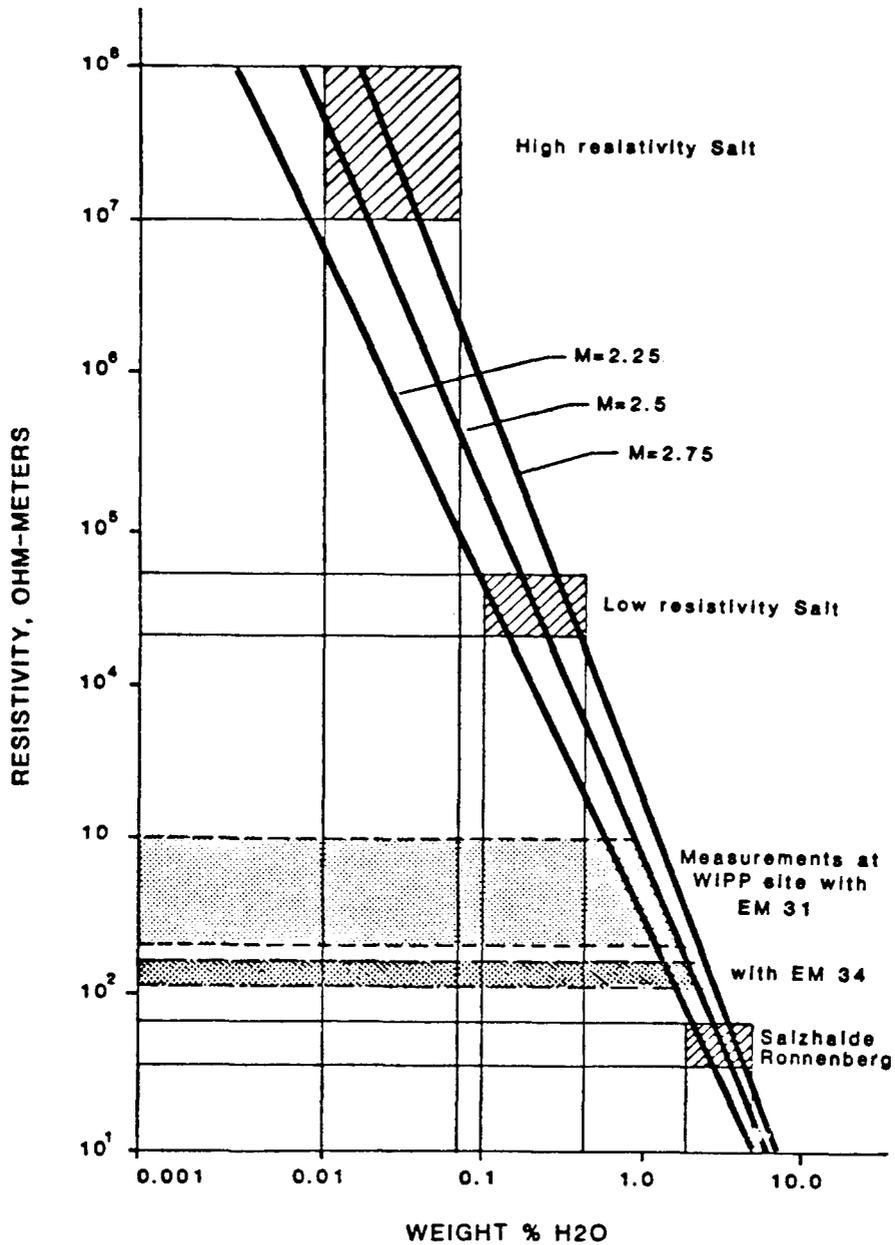


Figure 5. Apparent Resistivity versus Water Content

Explanation of Figure 5: This figure displays the relationship between apparent resistivity and water content for different factors of cementation or consolidation (m) for Archie's Law ($m = 2.5$ to 2.75 for Asse salt [Kessels et al., 1985]), crosshatched ranges are for resistivities of both Asse salt (high and low resistivity salt) and salt tailings pile (Salzhunde Ronnenberg) in which the water content was determined independently (Kessels et al., 1985); the stippled ranges are apparent resistivities of salt at the WIPP facility horizon; the water content of WIPP salt can be extrapolated from the intersection of the WIPP resistivities with the lines for the different consolidation factors.

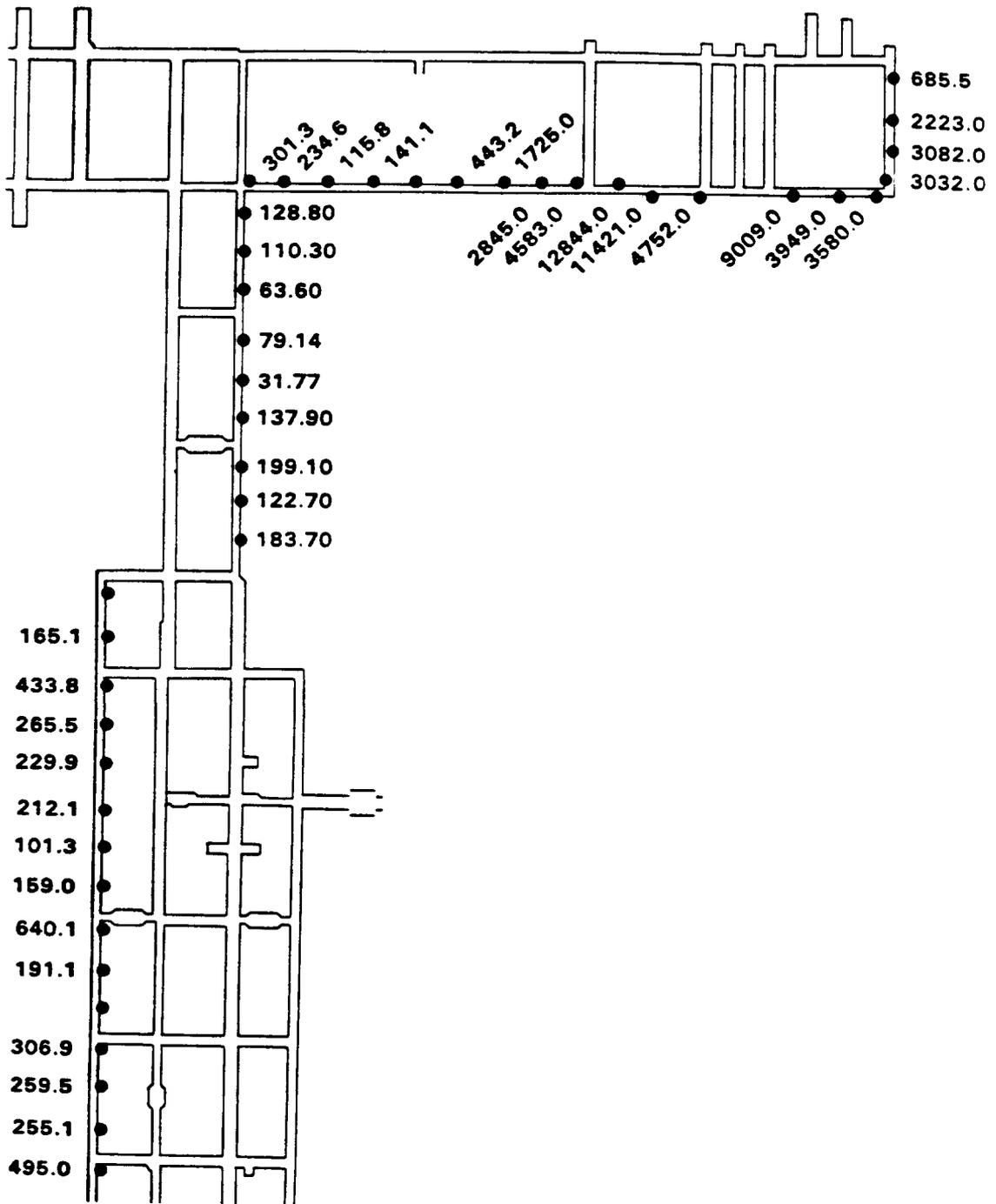


Figure 6. Apparent Resistivity Measurements in Ohm-Meters

HYDRAULIC TESTING

Brine Inflow

During the excavation of the underground WIPP facility, brine inflow was observed in shallow drillholes drilled from the repository (Popielak, 1983; Popielak et al., 1983) or as weeps on the ribs and back of the facility (Alcorn, 1983). The occurrence of brine inflow to the facility up to 1987 has been documented by Deal and Case (1987). The migration of brine into controlled boreholes in heated and unheated salt was described and modeled by Nowak (1986) and Nowak and McTigue (1987).

Gas-Flow Testing

Gas flow tests at the WIPP site were conducted from horizontal, vertical (both up and down), and angled boreholes drilled from the WIPP drifts (Stormont et al., 1987). Test fluid (nitrogen) was injected into the test interval (a portion of the borehole isolated by the packer system). The majority of the tests were either constant pressure flow tests or pressure decay tests conducted from single boreholes. The principal data from both constant pressure flow tests and pressure decay tests are flow rates of gas from the test interval into the surrounding formation. To facilitate comparisons of flow rates measured during different conditions (test pressure and test interval size), flow rates have been normalized to 0.07 MPa (10 psig) working pressure and a test interval of 1 m length and 13 cm diameter (Stormont et al., 1987). Permeabilities can be calculated by assuming that the rock is a homogeneous, isotropic porous medium and that the flow ideally obeys Darcy's Law.

Results of these gas flow tests in test intervals composed of rock salt are given in Figure 7 as the logarithm of the normalized

flow rate versus the distance of test interval from the excavation. Beyond 1 m the flow rates are consistently small (< 1 SCCM [1 standard cubic centimeter per minute]) and within 1 m of the excavation, flow rates vary by many orders of magnitude (1 to 10^3 SCCM).

When the test interval containing an interbed layer was distant from the excavation, the measured flow rates were low (< 1 SCCM). Relatively high flow rates occur when the interbed is within about 2 m of the excavation and the measurement has been made near the center of a drift or intersection. As illustrated in Figure 8, measured flow rates are always less than 1 SCCM when the measurement is made from near the rib, and the measurements made from near the center are greater than 1 SCCM. As shown in Figure 9, the wider the drift, the more flow is measured in the interbed.

Gas-flow measurements were conducted in the entryways to the first storage panel during May and June 1986 and repeated about one year later. The S1600 entryway is 4.3 m high by 4.6 m wide, and the S1950 entryway is 4.3 m high by 6.7 m wide. At these locations, the tests were performed in test intervals which contain the first significant interbeds above (Seam B) and below (MB139) the excavation (Figure 2). The tests were made near the center of the excavation. Initial measurements were made in these locations about 1 month after the excavation of the drifts. The results of the measurements are given in Table 1. Initially, during five of the six tests conducted in the rock above the drift, the formation produced gas, rather than accepting gas. One year later, the gas from the formation had dissipated, and flows less than 10 SCCM were measured. In tests conducted

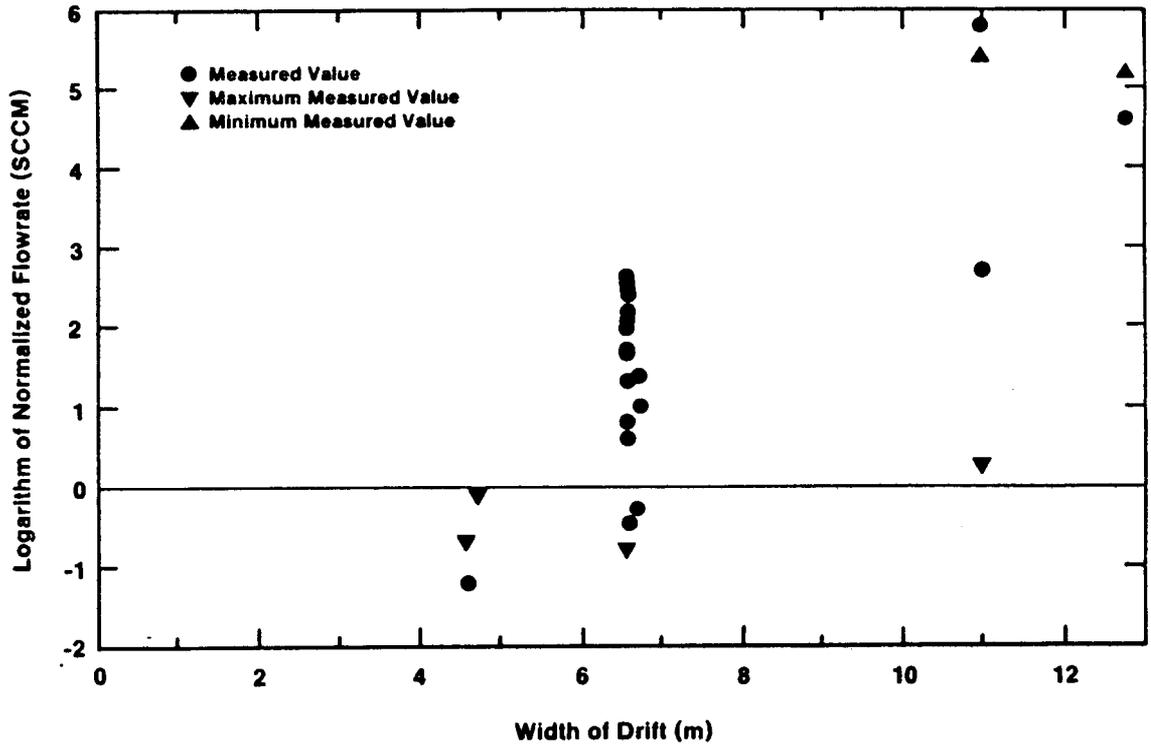


Figure 9. Width of Drift versus Gas Flow Rate in MB139

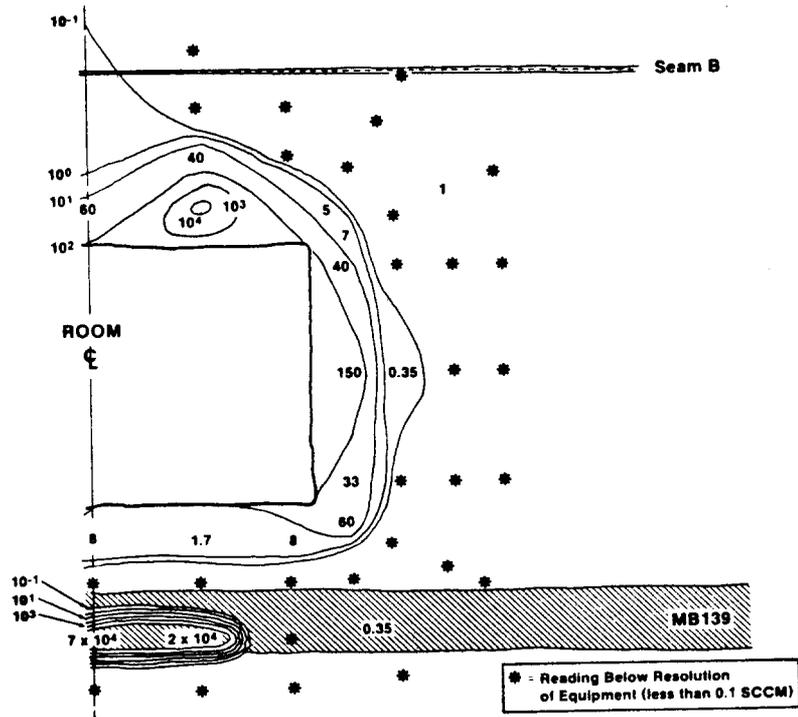


Figure 10. Contours of Gas Flow Rate around N1100 Drift at 4 yr

TABLE 1. NORMALIZED FLOW RATE (SCCM)

<u>LOCATION</u>	<u>1986 TESTS</u>	<u>1987 TESTS</u>
S1600 Drift (4.6 m wide) Seam B (up)	produced gas	0.3*
	produced gas	0.0*
	produced gas	0.0
MB139 (down)	0.06	0.3*
	<0.23	0.0
	0.11	0.3
S1950 Drift (11 m wide) Seam B (up)	0.01	0.0*
	produced gas	0.0
	produced gas	2.0
MB139 (down)	0.57	1300
	24.0	>10 ⁵
	11.8	>10 ⁵

* Below detection limits of instrumentation

Table 1. Normalized Flow Rates (SCCM)

in the rock below the drift, the initial gas injected flow rates were considerably greater in the wider drift. One year later, the flow rates nominally increased in the narrow drift but increased substantially in the wider drift.

In the 3.5 x 6 m N1100 drift an array of holes was drilled radially to a depth of about 10 m. Gas flow tests were conducted in numerous intervals along each hole. Figure 10 presents the results as contours of the normalized flowrate magnitude surrounding the drift. These results clearly demonstrate increased flow rates in the immediate vicinity of WIPP facility excavations. The contours in the halite suggest a circular or elliptical pattern centered on the drift with flow rates decreasing radially outward from the excavation. Anomalous zones of high flow were measured in MB139.

Tracer Gas Studies

Tracer gas studies were conducted from the N1420 drift in 1986 (Stormont et al., 1987) and the N1100 drift in 1987 (Peterson, 1987). The tests involved injecting a diluted tracer gas into a packed-off region of the test borehole and sampling the gas in surrounding boreholes for its arrival. In most instances, plastic tarps were fixed to the drift floor to catch gas moving from the test interval into the drift. The gas samples were analyzed for evidence of tracer, using electron capture gas chromatography. The flow path apertures were estimated as described by Peterson and Christensen (1980).

The purpose of the N1420 testing was to provide estimates of fracture continuity and apertures in MB139. The tracer arrivals indicate that the flow path width in MB139 in-

creases as the span of the drift increases--from an estimated 0.002 cm in a 6.6-m-wide drift to 0.04 cm at the intersection of two 11-m-wide drifts. It was also discovered during these tests that tracer gas was being transmitted from MB139 to the drift via the approximately 1 m thick layer of salt between MB139 and the floor of the drifts. Consistent with the inferences about MB139, it was found that apparent vertical flow paths in the salt increase with drift dimension--from 0.002 cm in a 6.6-m-wide drift to 0.02 cm at the intersection of two 11-m-wide drifts.

In the 6.6-m-wide N11000 drift, tracer gas studies were conducted in three boreholes:

one vertically up; one vertically down; and one horizontal. The test intervals were all in the salt within 1 m of the drift face. The tests in the vertically up and vertically down boreholes both indicate larger flow paths in the vertical direction (between the test interval and the drift). The test in the horizontal borehole indicated flow paths parallel to the drift face appreciably larger than those between the test interval and the drift. The inferred aperture of the flow path in all tests was small, about 1×10^{-6} m.

DISCUSSION

Possible Mechanical Processes Active in the DRZ

An underground opening extends a zone of influence into the host rock 5 to 6 times the radius of the opening around which the stress is redistributed (Brady and Brown, 1985). Within this zone of influence, the development of a zone (DRZ) of fractured, and dilatant rock around a mined opening is considered common in underground engineering (e.g., Peng, 1978; Gramberg and Roest, 1984; Brady and Brown, 1985). At the WIPP, the development of a DRZ has been confirmed by borehole observations, geophysical surveys, and gas flow tests. The origin of the DRZ is complex, with several processes competing or acting in concert. The stress field that develops in response to the opening influences the growth of the DRZ, but the geologic structure (e.g., preexisting fractures, clay, and anhydrite interbeds) around and near the opening is also important (Coates, 1981). The following processes may play a significant role in the development of the DRZ at the WIPP:

- Strain-rate dependent brittle failure of an elliptical zone of host rock immediately around the opening, in which the brittle failure envelope based on a strain-rate criterion is exceeded by the accelerated strain-rate adjacent to the opening (Dusseault et al., 1987).
- A volume of disturbed rock develops bounded by the excavation face and the elliptical surface of "the Active Opening" (Mraz, 1980). This volume of rock can separate (decouple) from the host rock along a shear zone that follows the elliptical surface of "the Active Opening."
- Shear induced by the opening along planes of weakness such as clay seams,

which are close to the excavation but do not intersect the excavation (Brady and Brown, 1985).

- A pressure arch develops symmetricaly above and below the opening, resulting in the redistribution of stresses and the development of stress concentration about the opening (Peng, 1978; Coates, 1981). Within the pressure arch, zones that are in tension develop within the host rock.

These processes give us a framework to understand the development of the DRZ at the WIPP. But at the WIPP, it has not been demonstrated rigorously, as yet, that these processes are active. The next step will be to examine how the processes outlined above can be used in modeling to numerically predict the growth of the DRZ. This step is needed to enhance the reliability of seal design and to determine whether the existing in-situ data and numerically derived data (e.g., stress fields around a WIPP opening) provide a sufficient base for predicting the development of the DRZ with time.

Hydraulic Characteristics of the DRZ

Basically, the DRZ can be characterized hydraulically in several ways:

- Within 2 m of the excavation, the DRZ is a zone in which increased flow rates and gas permeabilities are observed relative to the far field host rock.
- The increase in flow rate and permeability within the DRZ appears to be a function of rock type, size of the excavation, and age of the excavation.

- The DRZ has a lower fluid content than the far field rock salt. The fluid content of the DRZ also varies laterally along the length of the underground excavations. This lateral variation suggests that lateral variations in the permeability field and fracture density may exist.

To explain the gas flow results in halite, Stormont et al. (1987) postulated that a partially-saturated dilatant zone surrounds the WIPP excavation. In particular, a dilatant DRZ could account for gas flow in a formation that is thought to be brine-saturated in the undisturbed condition. The dilatant zone could include brine-saturated pores of sufficient size that their entry pressures are very low, permitting gas flow in our tests. An alternative explanation is that this zone is not completely brine-saturated, and the gas flows through the accessible gas-filled porosity. When the dilatant zone is created, accessible brine may be drawn into pore spaces by capillary pressure. This wetting would be uneven, because pore sizes differ, and the residual gas could then serve as gas flow channels. Evaporation of pore brine, expected to be enhanced by mine ventilation with relatively dry air, will also serve to create, maintain, or expand a partially-saturated zone. The gas-filled flow paths could be a small portion of the total porosity; gas can occupy as little as 1 to 2% of the total pore space and still provide a continuous path for gas flow (Geffen et al., 1951).

Implications of the DRZ:

On Previous Findings

In 1986 based on the preliminary study during the autumn of 1985, the WIPP project participants (the WIPP Project Office [WPO], Bechtel, SNL, and Westinghouse) concluded (Lappin, 1986) that the WIPP facility horizon should not be moved in

response to the observed fractures in Room T (see section above on Chronology of Fracture Observations) . The project also concluded that the width of the barrier pillars should be maintained at 60 m and that the rooms and drifts be kept at the minimal size compatible with operation of the waste emplacement equipment. The rationale for the last two steps was to provide for seal emplacement with the minimum of disturbed rock.

The studies conducted since the autumn of 1985 were intended to support the conclusions reached in 1986. Since fractures and disturbed rock are observed throughout the underground facility and at both facility horizons, development of a DRZ would probably occur at any horizon within the salt units at the WIPP. Therefore, as concluded in 1986, moving the facility to another horizon would not greatly affect the growth of a DRZ. The continuing studies reiterate that the size of the DRZ increases with the age and size of the openings. This relationship is consistent with the 1986 conclusion to keep the openings to a minimal size. However, this conclusion is in conflict with the need to provide a stable back for mining operations. To stabilize the back in active drifts and rooms such as tramways, the back will have to be periodically shaved, which probably will result in a larger opening than designed.

On Observed Closure

From the porosity field surrounding the WIPP drifts inferred from gas flow measurements, Stormont et al. (1987) derived a component of closure due to dilatancy. This dilatant component of closure as inferred from gas flow measurements could contribute, along with creep closure, to the total closure observed. Morgan et al. (1986) documented that calculated closures on creep laws underpredicted the observed

closure by a factor of three at the WIPP. The recognition of a dilatant strain component could to a degree reduce the differences between the observed closures and the calculated closures based solely on creep laws.

On Room Stability

The studies described in this report and in the work of Francke (1987) show that a DRZ will develop around all of the underground workings, given sufficient time. Therefore, Mining Operations has established the Openings Maintenance Program to study how the DRZ forms and how to best control it. The development of the DRZ has already impacted maintenance for several underground excavations. The primary concern of Mining Operations is to maintain a safe back and rooms from which the retrieval of waste will not be impeded during the first 5 to 10 yr by failure of the back. An additional consideration will be the maintenance of room and tramway tolerances over the extended periods of operations (15-25 yr). This maintenance may require trimming the floor into the fractured anhydrite of MB139 in order to maintain the required thickness of salt in the back for stability. The fractured anhydrite in the floor may require further maintenance. As we gain experience underground at the WIPP, we will know the magnitude of the effects on operations due to the DRZ, but we now understand that the DRZ will develop throughout the underground facility and will affect operations to some extent.

On Seal Design

The major considerations in rock mass sealing are the seal/rock interface and in the DRZ in the vicinity of the seals. A substantial DRZ that persists in time could provide a path through which fluid could bypass the seals. If a DRZ is not healed with time, it

could interconnect the waste disposal panels with other portions of the facility. Delineation of the DRZ is required to determine what, if any, remedial action is necessary to establish effective seals. Stress buildup in the vicinity of a relatively stiff inclusion (e.g., concrete or consolidated salt seals) may reverse the disturbance by forcing the rock back together, thereby decreasing its permeability. Preliminary studies by Arguello and Torres (1988) suggest that stresses within the host rock around a seal build up toward lithostatic. Qualitatively, the stress buildup should initiate healing, but the rates and amount of permeability reduction due to the healing process are not well known. The behavior of anhydrite is important, since a major fracture system develops within MB139, and fractures in anhydrite (with its increased strength and slower solution and reprecipitation relative to halite) will heal at a different rate than halite. Also, lateral displacement (shear) occurs across the fractures in the DRZ. This shear is such that the asperities on opposite walls of the fracture no longer match. This mismatch will retard healing of the fracture. If the healing of the DRZ does not occur fast enough, excavation of the excessively transmissive portion of the DRZ at strategic locations is an option.

On Performance Assessment

This study does not directly address the effects of a DRZ on Performance Assessment of the WIPP facility, but from this study some questions arise that would be of importance. These questions are whether the DRZ would:

- Provide seal bypass
- Affect brine influx
- Act as a fluid sink

A seal bypass as described above would develop if the DRZ provided an interconnected zone of permeability higher than the host rock, which the seal design did not adequately close. Brine influx may be affected by the DRZ by the alteration of the stress gradients around the openings with the initiation of fracturing and the development of discrete, high permeability zones. A sink for both brine and gas could be provided by a network of fractures and zones of higher permeability that develops in the DRZ. This sink would not only accept formation fluids but also fluids from mining operations (water-jet cutter and the water

spread from the shaft sumps) and from the waste form. Gases generated from the waste and other operations underground could also collect in the sink provided by the DRZ.

To ascertain the effects of these questions on Performance Assessment, the continued characterization of the DRZ needs to interface with the seal design and testing. Also, more study of fracture healing, both in anhydrite and halite, is needed to understand the rates of fracture closure and permeability reduction that would develop with time during the closure of the repository.

SUMMARY

Effects of the DRZ on Rock Properties and Behavior

Rock salt that experiences excessive strain or is decoupled from the far-field host rock will no longer behave like intact rock salt. Such changes in behavior and properties are observed in hydraulic tests and geophysical measurements within the DRZ that has developed around the underground WIPP facility. The DRZ is characterized by distinct changes in permeability and water content of the host rock from the excavation surface out 1 to 2 m from the excavation. Geophysical studies of resistivities suggest that the permeability and/or fluid content of the DRZ also varies laterally.

Character of the Disturbed Rock Zone

Underground excavations at the WIPP site result in the development of a DRZ. This DRZ can be envisioned as a series of elliptical structures centered on the excavation (Figure 11, modified from Gramberg and Roest, 1984). The structures developed within the DRZ are characterized by mesoscopic and microscopic fracturing in both the halite and anhydrite interbeds at the facility horizon in response to stresses developed during excavation or excessive

strain induced by creep. The rock salt in the ribs develops nearly vertical fractures parallel to the drift due to the low radial stresses near the ribs. These fractures may become extensive enough to result in spalling.

Effects of the Age and Size of the Excavation

The magnitude of the structures developed within the DRZ appears to be a function of both the size and the age of the opening. In the wider openings, within a 5 yr period fractures are observed at all locations. Around these openings, a zone of the host rock has separated (decoupled) from the surrounding rock and has become stress relieved. In this case, the effective size of the opening, which includes the excavation and the decoupled rock around it (the *Active Opening* of Mraz [1980]), is not defined by the excavation but by the zone of the fractures that separate the DRZ from the intact host rock. In the narrower openings at the WIPP, within the same 5 yr period fracturing is not observed at all locations. However, with time the narrow rooms show an increasing distribution of fractures (50% of areas after 3 years and 70% after 5 years).

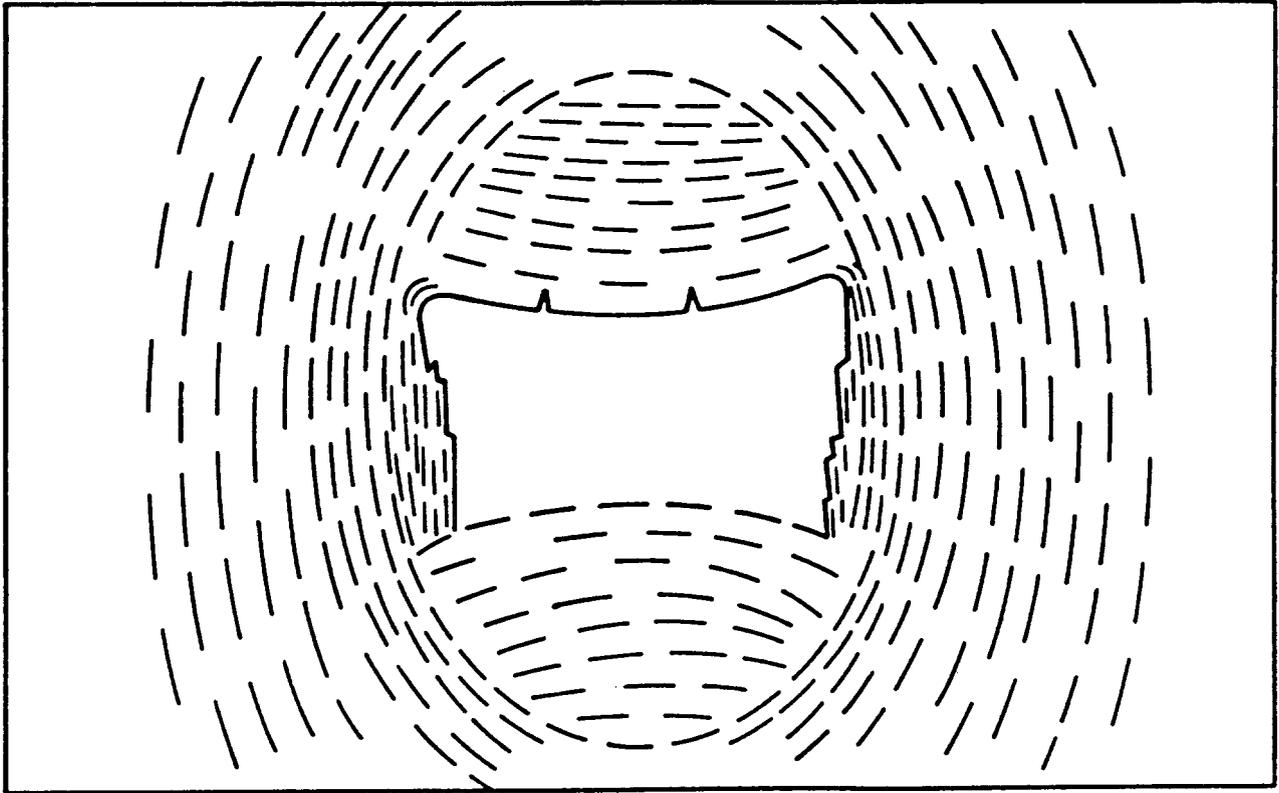


Figure 11. Fracture Pattern around an Excavation in Salt
Modified from Fig. 8 in Gramberg and Roest (1984) as observed in Asse mine

REFERENCES

- Alcorn, S. R., 1983, Occurrence of Brine "Weeps" in the WIPP Facility, Memo to D. K. Shukla, dated October 3, 1983, WIPP Support Contractor Project No. NM78-648-080A
- Arguello, J. G., and Torres, T., 1988 WIPP Panel Entryway Seal - Numerical Simulation of Seal Component/Formation Interaction for Preliminary Design Evaluation, Sandia Report, SAND87-2591
- Bechtel National, Inc., 1986, Interim Geotechnical Field Data Report, DOE-WIPP-221, prepared for the U. S. Department of Energy by Bechtel National, Inc., San Francisco, California
- Borns, D. J., 1985, Marker Bed 139: A Study of Drillcore from a Systematic Array, Sandia Report, SAND85-0023
- Brady, B. H. G., and Brown, E. T., 1985, Rock Mechanics for Underground Mining, George Allen and Unwin, London, 527p
- Coates, D. F., 1981, Rock Mechanics Principles, CANMET, Energy Mines and Resources Canada, Ottawa, Monograph 874
- Cook, C. W., 1982, Underground Scanning with an Impulse Radar, Sandia Report, SAND82-0470, 48 p.
- Deal, D. E., and Case, J. B., 1987, Brine Sampling and Evaluation: Phase I Report, Report No. DOE-WIPP-87-008, U. S. Department of Energy (Waste Isolation Pilot Plant), Carlsbad, New Mexico
- Dusseault, M. B., Rothenburg, L., and D. Z. Mraz, 1987, The design of openings using multiple mechanism viscoplastic, 28th US Symposium on Rock Mechanics, 633-642
- Francke, C., 1987, Excavation Effects and Fracture Mapping, input to 1987 GFDAR, memorandum to R. McKinney, IT Corporation, WIPP site, August 18, 1987
- Geffen, T. M., Owens, W. W., Parrish, D. R. and Morse, R. A., 1951, Experimental investigation of factors affecting laboratory relative permeability measurements, Petroleum Transactions, AIME, 192
- Gramberg, J., and Roest, J. P. A., 1984, Cataclastic effects in rock salt: laboratory and in situ measurements, Commission of the European Communities, EUR 9258 EN, 68p
- Hudson, J., 1987, personal communication to J. S. Stormont on USGS moisture and density measurements in bedded rock salt at the WIPP site
- Keller, G. V., Skokan, C. K., Andersen, H. T., Pfeifer, M. C., Keller, S. D. Keller, and Kim, K. D., 1987, Final Report: Studies of Electrical and Electromagnetic Methods for Characterizing Salt Properties at the WIPP Site, New Mexico, Contractor report to Sandia National Laboratories (Contract No. 04-1295), Department of Geophysics, Colorado School of Mines
- Kessels, W., Flentge, I., Kolditz, H., 1985, DC geoelectric sounding to determine water content in the salt mine ASSE (FRG): Geophysical Prospecting, 33, 436-446
- Lappin, A. R., 1986, Draft SNLA/Bechtel/W/IT recommendations arising from 2/13/86 meeting on the present status of excavation effects studies, memo to distribution dated 2/19/86
- Morgan, H. S., Stone, C. M., and Krieg, R. D., 1986, An evaluation of WIPP Structural Modeling Capabilities Based on Comparisons with South Drift data, Sandia Report, SAND85-0320
- Mraz, D., 1980, Plastic behavior of salt rock utilized in designing a mining method, CIM Bulletin, 73, 11-123, 1980
- Nowak, E. J., 1986, Preliminary Results of Brine Migration Studies in the Waste Isolation Pilot Plant (WIPP), Sandia Report, SAND86-0720

- Nowak, E. J., and McTigue, D. F., 1987, Interim results of brine transport studies in the Waste Isolation Pilot Plant (WIPP), Sandia Report, SAND87-0880
- Peng, S. S., 1978, Coal Mine Ground Control, John Wiley and Sons, New York, 450p
- Peterson, E. W., 1987, Summary of N1100 Drift Tracer Gas Travel Time Tests, personal communication (23 October 1987) to J. C. Stormont (SNL)
- Peterson, E. W., and Christensen, C., 1980, Analysis of Bell Canyon Test Results, Sandia Report, SAND80-058C,
- Pfeifer, M. C., 1987, Multicomponent Underground DC Resistivity Study at the Waste Isolation Pilot Plant, Southeast New Mexico, M. S. Thesis, Colorado School of Mines, T-3372
- Popielak, R. S., 1983, Gas Testing Program: Phase II, Task 2, memo to D. K. Shukla et al., dated May 9, 1983, WIPP Support Contractor Project No. NM78-648-080B
- Popielak, R. S., Olsen, R. L., and Smith, Z. A., 1983, Results of Gas Testing in WIPP Underground Drifts, March 6-23, 1983, Memo to D. K. Shukla, dated April 13, 1983, WIPP Support Contractor Project No. NM78-648-090B
- Powers, D. W., Lambert, S. J., Shaffer, S.-E., Hill, L. R., and Weart, W. D., 1978, Geological Characterization Report, Waste Isolation Pilot Plant (WIPP) Site, Southeastern New Mexico, Sandia Report, SAND78-1596
- Stormont, J. C., Peterson, E. W., and Lagus, P. L., 1987, Summary of and Observations about WIPP Facility Horizon flow Measurements through 1986, Sandia Report, SAND87-0176
- Unterberger, R. R., 1981, Subsurface Radar Applications in the Delaware Basin, Sandia Report, SAND81-7153

DISTRIBUTION:

U. S. Department of Energy (5)
Office of Civilian Radioactive Waste Management
Office of Geologic Repositories
Forrestal Building
Washington, DC 20585

Stephen H. Kale - RW-20
Associate Director
T. H. Isaacs - RW-20
Deputy associate Director
James C. Bresee - RW-22
Director,
Repository Coordination
Division.
Ralph Stein - RW-23
Director, Engineering
& Geotechnology
James P. Knight - RW-24
Director, Siting, Licensing,
and Quality Assurance

U. S. Department of Energy (3)
Albuquerque Operations Office
P. O. Box 5400
Albuquerque, NM 87185

Bruce G. Twinning
J. E. Bickel
D. G. Jackson, Director,
Public Affairs Division

U. S. Department of Energy
Albuquerque Operations Office
P. O. Box 5400
Albuquerque, NM 87185
National Atomic Museum Library

U. S. Department of Energy (9)
WIPP Project Office (Carlsbad)
P. O. Box 3090
Carlsbad, NM 88221

J. Tillman (4)
A. Hunt
T. Lukow (2)
V. Daub
B. Young

U. S. Department of Energy
Research & Technical Support Division
P.O. Box E
Oak Ridge, TN 37830
D. E. Large

U. S. Department of Energy
Richland Operations Office
Nuclear Fuel Cycle & Production Division
P.O. Box 500
Richland, WA 99352
R. E. Gerton

U.S. Department of Energy (4)
Office of Defense Waste and
Transportation Management
Washington, DC 20545
G. Daly ----- DP-124
M. Duff -----DP-123
A. Follett -----DP-121
J. Mather ----- DP-121

U.S. Department of Energy (2)
Idaho Operations Office
Fuel Processing and Waste
Management Division
785 DOE Place
Idaho Falls, ID 83402

U.S. Department of Energy (4)
Savannah River Operations Office
Waste Management Project Office
P.O. Box A
Aiken, SC 29801
S. Cowan
W. J. Brumley
J. R. Covell
D. Fulmer

U.S. Department of the Interior
959 National Center
Geological Survey
Reston, Virginia 22092
E. Roedder

U.S. Nuclear Regulatory Commission (4)
Division of Waste Management
Mail Stop 623SS
Washington, DC 20555
Michael Bell
Hubart Miller
Jacob Philip
NRC Library

U.S. Geological Survey

Special Projects
MS 913, Box 25046 Denver Federal Center
Denver, CO 80255
R. Snyder

U.S. Geological Survey
Conservation Division
P.O. Box 1857
Roswell, NM 88201
W. Melton

U.S. Geological Survey (2)
Water Resources Division
4501 Indian School Road NE
Suite 200
Albuquerque, NM 87110
Cathy Peters

State of New Mexico (3)
Environmental Evaluation Group
Suite F-2
7007 Wyoming Blvd., NE
Albuquerque, NM 87109
Robert H. Neill, Director

State of New Mexico (3)
Environmental Evaluation Group
505 North Main Street
Carlsbad, New Mexico 88221-3149
NM Department of Energy & Minerals
P.O. Box 2770
Santa Fe, NM 87501
Kasey LaPlante, Librarian

New Mexico Bureau of Mines (2)
and Mineral Resources
Socorro, NM 87801
F. E. Kottolowski, Director
J. Hawley

Argonne National Laboratory (1)
Attn: D. Hambeley
9700 South Cass Avenue
Argonne, IL 60439
D. Hambeley

Battelle
Engineering Development Section
OWTD
7000 South Adams Street
Willowbrook, Illinois 60521
C. B. Brumleve

Battelle Pacific Northwest Laboratories (6)
Battelle Boulevard
Richland, WA 99352
J. Nelson (HWVP)
P. Salter
W. W. Schultz
D. J. Bradley
J. Relyea
R. E. Westerman
S. Bates
H. C. Burkholder
L. Pederson

Bechtel Inc. (3)
P.O. Box 3965
45-11-B34
San Francisco, CA 94119
E. Weber
M. Bethard
H. Taylor

Brookhaven National Laboratory (1)
Associated Universities, Inc.
Attn: Paul W. Levy, Senior Scientist
Upton, NY 11973
Paul W. Levy, Senior Scientist

E. I. Dupont de Nemours Company (6)
Savannah River Laboratory
Aiken, SC 29801
N. Bibler
E. L. Albenisius
M. J. Plodinec
G. G. Wicks
C. Jantzen
J. A. Stone
J. G. McCray

Dupont Company
Building 704-S
Savannah River Plant
Aiken, SC 29808
R. G. Baxter

INTERA Technologies, Inc. (4)
6850 Austin Center Blvd., #300
Austin, TX 78731
G. E. Grisak
J. F. Pickens
A. Haug
A. M. LaVenue

INTERA Technologies, Inc.

P.O.Box 2123
Carlsbad, NM 88221
Wayne Stensrud

IT Corporation (2)
P.O. Box 2078
Carlsbad, NM 88221
R. McKinney

IT Corporation (3)
2340 Alamo, SE
Suite 306
Albuquerque, NM 87106
W. R. Coons
S. Niou
J. Myers

Los Alamos Scientific Laboratory
Attn: B. Erdal, CNC-II
Los Alamos, NM 87545
B. Erdal, CNC-II

Oak Ridge National Laboratory (4)
Box Y
Oak Ridge, TN 37830
R. E. Blanko
E. Bondietti
C. Claiborne
G. H. Jenks

RE/SPEC, Inc. (7)
P.O. Box 725
Rapid City, SD 57701
P. F. Gnirk
L. L. Van Sambeek
D. B. Blankenship
T. Brandshaug
G. Callahan
T. Pfeifle
J. L. Ratigan

RE/SPEC, Inc.
P.O. Box 14984
Albuquerque, NM 87191
S. W. Key

Rockwell International (1)
Rocky Flats Plant
Golden, CO 80401
C. E. Wickland

Rockwell International (3)
Atoms International Division

Rockwell Hanford Operations
P.O. Box 800
Richland, WA 99352
J. Nelson (HWVP)
P. Salter
W. W. Schultz

SAIC
101 Convention Center Dr.
Las Vegas, NV 89109
George Dymmel

Systems, Science, and Software (2)
Box 1620
La Jolla, CA 92038
E. Peterson
L. Lagus

Westinghouse Electric Corporation (7)
P.O. Box 2078
Carlsbad, NM 88221
W. Moffit
V. DeJong
W. Chiquelin
T. Dillon
V. Likar
R. Kehrman
Library

Woodward-Clyde Consultants
Library Western Region
3 Embarcadero Center, Suite 700
San Francisco, CA 94111
Anne T. Harrigan, Librarian
Charles Taylor

Hobbs Public Library
509 N. Ship Street
Hobbs, NM 88248
Ms. Marcia Lewis, Librarian

New Mexico Tech
Martin Speere Memorial Library
Campus Street
Socorro, NM 87810

New Mexico State Library
P.O. Box 1629
Santa Fe, NM 87503
Ms. Ingrid Vollenhofer

Zimmerman Library
University of New Mexico

Albuquerque, NM 87131
Zanier Vivian

WIPP Public Reading Room
Atomic Museum
Kirtland East AFB
Albuquerque, NM 87185
Ms. Gwynn Schreiner

WIPP Public Reading Room
Carlsbad Municipal Library
101 S. Hallagueno St.
Carlsbad, NM 88220
Lee Hubbard, Head Librarian

Thomas Brannigan Library
106 W. Hadley St.
Las Cruces, NM 88001
Don Dresp, Head Librarian

Roswell Public Library
301 N. Pennsylvania Avenue
Roswell, NM 88201
Ms. Nancy Langston

University of Arizona
Department of Nuclear Engineering
Tucson, AZ 85721
J. G. McCray

Univ. Of Arizona (2)
Dept. of Mining and Geological
Engineering
Tuscon, AZ 85721
J. J. K. Daemen
B. Sternberg

Prof. J. Rosenfeld
Dept. of Earth and Space Sciences
UCLA
Los Angeles, CA 900024

University of New Mexico (2)
Geology Department
Albuquerque, NM 87131P255D
D. G. Brookins
Library

The Pennsylvania State University
Materials Research Laboratory
University Park, PA 16802
Della Roy

Texas A&M University
Center of Tectonophysics
College Station, TX 77840
John Handin

University of Texas at El Paso
Department of Geological Sciences
El Paso, TX 79968
D. W. Powers

Bureau of Economic Geology (3)
The University of Texas
University Station, Box X Austin, Texas 78712
M. P. A. Jackson
J. Raney
S. Hovorka

Dept. of Civil Engineering (2)
The Univ. of Texas at Austin
Austin, Texas 78712
Priscilla P. Nelson
Kenneth H. Stokoe

National Academy of Sciences, WIPP Panel:
Konrad B. Krauskopf
Stanford University
Department of Geology
Stanford, CA 94305

Frank L. Parker
Vanderbilt University
Department of Environmental and
Water Resources Engineering
Nashville, TN 37235

John O. Blomeke
Oak Ridge National Laboratory
P.O. Box X
Oak Ridge, TN 37830

John D. Bredehoeft
Western Region Hydrologist
Water Resources Division
U.S. Geological Survey
345 Middlefield Road
Menlo Park, CA 94025

Dr. Karl P. Cohen
928 N. California Avenue
Palo Alto, CA 94303

Fred M. Ernsberger
1325 N.W. 10th Avenue

Gainesville, FL 32611

Rodney C. Ewing
University of New Mexico
Department of Geology
Albuquerque, NM 87131

Charles Fairhurst
University of Minnesota
Department of Geological Sciences
Minneapolis, MN 55455

William R. Muehlberger
University of Texas at Austin
Department of Geological Sciences
Austin, TX 78712

D'Arcy A. Shock
233 Virginia
Ponca City, OK 74601

National Academy of Sciences (2)
Committee on Radioactive Waste Management
2101 Constitution Avenue, NW
Washington, DC 20418
Peter Meyers
Remi Langum

Studiecentrum Voor Kernenergie (2)
Centre D'Energie Nucleaire
SCK/CEN
Boeretang 200
B-2400 Mol
BELGIUM
Mr. A. Bonne
Pierre Van Iseghem

Atomic Energy of Canada, Ltd. (2)
Whiteshell Research Estab.
Pinewa, Manitoba, CANADA
ROE 1LO
Peter Haywood
John Tait

Ontario Hydro Research Lab
800 Kipling Avenue
Toronto, Ontario, CANADA
M8Z5S4
Dr. D. K. Mukerjee

Centre D'Etudes Nucleaires
De La Valle Rhone
CEN/VALRHO

SDHA BP 171
30205 Bagnols-Sur-Ceze
FRANCE
Claude Sombret

OECD Nuclear Energy Agency
Division of Radiation Protection
and Waste Management
38, Boulevard Suchet
75016 Paris, FRANCE
Jean-Pierre Olivier

Fred Karlsson
Institut fur Tieflagerung (4)
Theodor-Heuss-Strasse 4
D-3300 Braunschweig
FEDERAL REPUBLIC OF GERMANY
K. Kuhn
N. Jockwer
H. Gies
P. Faber

Bundesanstalt fur Geowissenschaften
und Rohstoffe
Postfach 510 153
3000 Hannover 51
FEDERAL REPUBLIC OF GERMANY
Michael Langer

Hahn-Mietner-Institut fur Kernforschung (2)
Glienicke Strasse 100
1000 Berlin 39
FEDERAL REPUBLIC OF GERMANY
Werner Lutze
Klaus Eckart Maass

Bundesministerium fur Forschung und
Technologie
Postfach 200 706
5300 Bonn 2
FEDERAL REPUBLIC OF GERMANY
Rolf-Peter Randl

Physikalisch-Technische Bundesanstalt (2)
Bundesanstalt 100, 3300 Braunschweig
FEDERAL REPUBLIC OF GERMANY
Helmut Rothemeyer
Peter Brenneke

Kernforschung Karlsruhe (3)
Postfach 3640
7500 Karlsruhe
FEDERAL REPUBLIC OF GERMANY

R. Koster	6300	R. W. Lynch
Reinhard Kraemer	6310	T. O. Hunter
K. D. Closs	6313	T. Blejwas
	6313	L. Sheppard
British Nuclear Fuels, plc	6330	W. D. Weart
Risley, Warrington, Cheshire WA3 6AS	6330	G. R. Romero
1002607 GREAT BRITAIN	6331	A. R. Lappin
D R Knowles	6331	R. L. Beauheim
	6331	D. J. Borns (15)
Japan Atomic Energy	6331	P. B. Davies
Research Institute	6331	M. Gonzales
Tokai-Mura, Ibaraki-Ken	6331	S. J. Lambert
319-11 JAPAN	6331	R. Z. Lawson
Shingo Tashiro	6331	L. Jensen
	6331	K. L. Robinson
Netherlands Energy Research Foundation ECN (2)	6331	M. D. Siegel
3 Westerduinweg	6332	L. D. Tyler
P.O. Box 1	6332	R. Beraun
1755 ZG Petten	6332	R. V. Matalucci
THE NETHERLANDS	6332	M. A. Molecke
Tuen Deboer, Mgr.	6332	D. E. Munson
L. H. Vons	6332	J. E. Nowak
	6332	R. J. Roginski
Svensk Karnbransleforsorjning AB	6332	J. C. Stormont (10)
Project KBS	6332	T. M. Torres
Karnbranslesakerhet	6332	Sandia WIPP Central Files (800 GEOPH) (10)
Box 5864	6333	T. M. Schultheis
10248 Stockholm, SWEDEN	6334	D. R. Anderson
	6334	S. Bertran-Howery
Swedish Geological Co	6334	K. Brinster
Pusterviksgatan 2 - S-413 01	6334	L. Brush
Goteberg, SWEDEN	6334	M. S. V. Chu
Anders Winberg	6334	L S Gomez
	6334	R. L. Hunter
Sandia Internal:	6334	R. D. Klett
	6334	R. R. Richard
1510 J. W. Nunziato	6334	A. Rutledge
1520 C. W. Peterson	7100	C. D. Broyles
1521 R. D. Krieg	7110	J. D. Plimpton
1521 H. S. Morgan	7116	S. R. Dolce
1521 J. G. Arguello	7116	C. W. Cook
3141 S. A. Landenberger (5)	7120	M. J. Navratil
3151 W. L. Garner (3)	7125	R. L. Rutter
3154-1 C. H. Dalin, For: DOE/TIC (8)	7125	J. J. Loukota
6000 D. L. Hartley	7125	J. T. McIlmoyle
6230 W. C. Luth	7130	J. O. Kennedy
6232 W. R. Wawersik	7133	R. D. Statler
6232 D. Zeuch	7133	J. W. Mercer
6233 T. M. Gerlach	7133	H. C. Walling
6233 W. Casey	7135	P. D. Seward
6233 J. L. Krumhansl	8524	P. W. Dean (SNLL Library)
6233 C. L. Stein		