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Title: The Excavation Effects Program at the Waste Isolation Pilot Plant

Author(s): Christopher T. Francke, Liane J. Terrill

To be published in and/or presented at (meeting, date, sponsor, etc.) International Congress on Mine Design, 23-26 August, 1993, Queen's University-Kingston, Ontario, Canada

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Waste Isolation Division
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Author Christopher T. Francke, Liane J. Terrill

The document is:

M

- [ ] Approved as presented.
- [x] Approved with corrections needed.
- [ ] Disapproved (see attached rationale).
- [ ] Approved, travel expenses disapproved

Anita B. Dervo
Public Affairs Coordinator

11/25/92
Date

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TITLE: The Excavation Effects Program at the Waste Isolation Pilot Plant

AUTHOR: Christopher T. Francke, Liane J. Terrill   PHONE:

PRESENTATION TO: International Congress on Mine Design, Queen's University-Kingston, Ontario, Canada   DATE OF PRESENTATION: Aug. 23 - 26, 1993

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The Excavation Effects Program at the Waste Isolation Pilot Plant

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ABSTRACT:
Excavation effects are the observable evidence of damage incurred by the rock mass due to the removal of material during mining. Excavation effects of primary concern to ground control and maintenance engineers are the displacement of the rock and the formation of various types of fractures and separations near the excavation. Well established and relatively simple techniques already exist for measuring rock displacements. Characterization of fracture systems surrounding excavations is a much more difficult problem, especially in creeping materials such as halite for which the extent and orientation of fracturing may change continually with time. Many indirect geophysical methods, such as ground probing radar, are available for this purpose, but they are usually quite costly and require equipment and expertise normally not available at a production mine.

An inexpensive technique developed for characterizing fracture systems surrounding underground excavations at the Waste Isolation Pilot Plant (WIPP) provides a quick and systematic method that does not require special expertise to use successfully. WIPP is being developed near Carlsbad, New Mexico, for the disposal of transuranic nuclear wastes in underground excavations in salt 2150 feet below the surface. The unique mission of WIPP requires access drifts to remain open and safe for up to 40 years, which in turn requires a complex ground control plan. The ability to fully characterize the fracture systems in the roof and floor of excavations, and to predict the intensity of fracturing that will develop over the life of an excavation is fundamental to the design of a ground control system. The technique used at WIPP consists of direct observation of fractures in small-diameter jacklegged boreholes via a simple, inexpensive tool made from materials found in any mine maintenance shop. This successful technique provided the basic information on the deformation mechanisms acting at WIPP and was critical in the design of the ground support system used throughout the underground. It also has contributed to accurate prediction of the size and shape of roof falls that were allowed to occur for experimental purposes in unsupported, barricaded drifts. The borehole survey technique provides information on the shape, extent, and degree of fracturing and horizontal movements, as well as the rate of fracture

development. A correlation between excavation age and fracture development has been established using data from this method. This technique is ideal for use at commercial mines where fracturing and ground support are a concern.

1.0 INTRODUCTION

Ground control is a basic, fundamental problem that must be considered by every underground operation. The magnitude of ground control problems at a facility directly effects production rates, operational costs, facility design, engineering effort, and operational safety. Underground operations in salt at the Waste Isolation Pilot Plant (WIPP) are especially sensitive to ground control concerns where they affect criteria for operational safety and waste retrievability in an ever changing operational environment. Programs were implemented at WIPP to monitor the response of the salt to excavations. The information from these programs is important to the continued safe operation of the plant, as well as to the mining industry as a whole.

1.1 Waste Isolation Pilot Plant

The Waste Isolation Pilot Plant was authorized by Congress in 1979 (Public Law 96-164) to provide "...a research and development facility to demonstrate the safe disposal of radioactive wastes resulting from the defense activities and programs of the United States exempted from regulation by the Nuclear Regulatory Commission" (U.S. DOE, 1992). The WIPP is intended to receive, handle, and permanently dispose of transuranic waste. To fulfill this mission, the U.S. Department of Energy (DOE) is constructing a full scale facility to demonstrate both technical and operational principles of the permanent isolation of transuranic waste. The facility is also designed for in-situ studies and experiments in salt.

1.2 Location

The Waste Isolation Pilot Plant is located in the United States in southeastern New Mexico about 50 km (30 miles) east of Carlsbad. The surface facilities have been built on the flat to gently rolling hills that are characteristic of the Los Medanos (sand hills) area. The underground facilities are being excavated approximately 655 meters (2,150 feet) beneath the surface. Figure 1 shows a plan view of the underground facilities at the WIPP site.

1.2 Geology

The WIPP facility excavations are located in the Permian Salado Formation, a thick sequence of bedded evaporite deposits. The formation is composed predominantly of halite containing minor amounts of clay, anhydrite, and polyhalite. Several areally persistent layers of anhydrite and

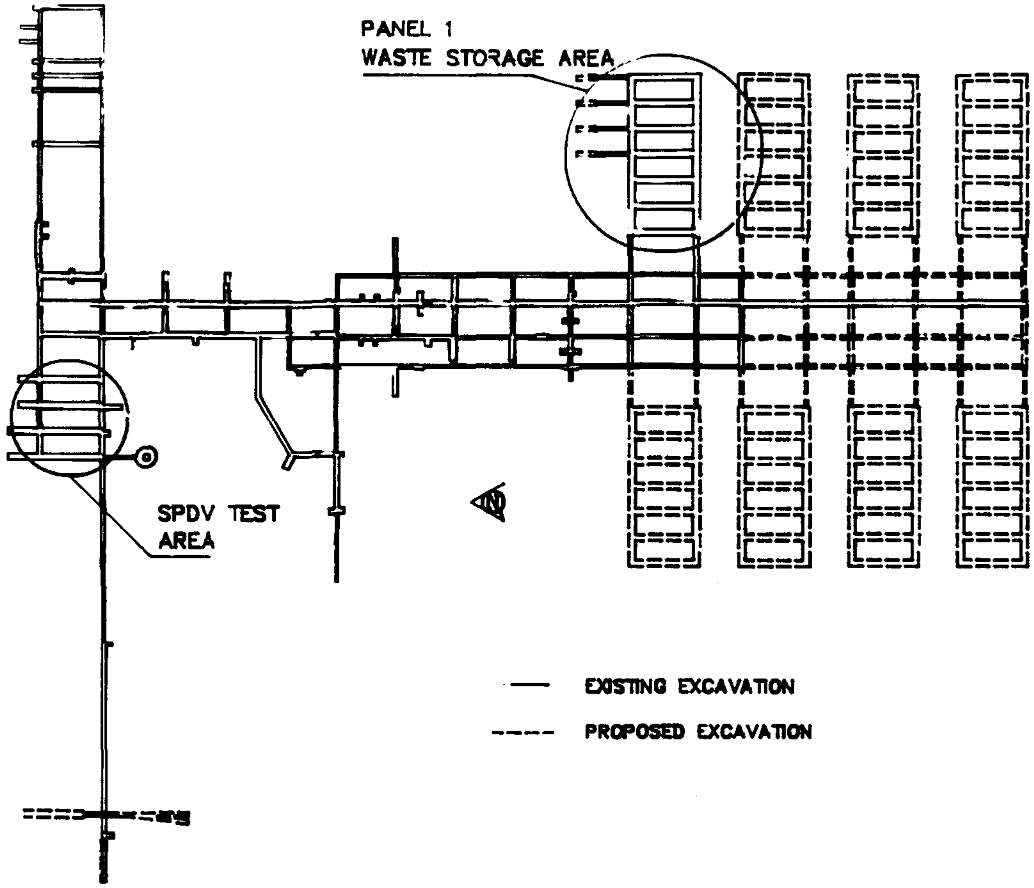

Figure 1. WIPP Mine Plan

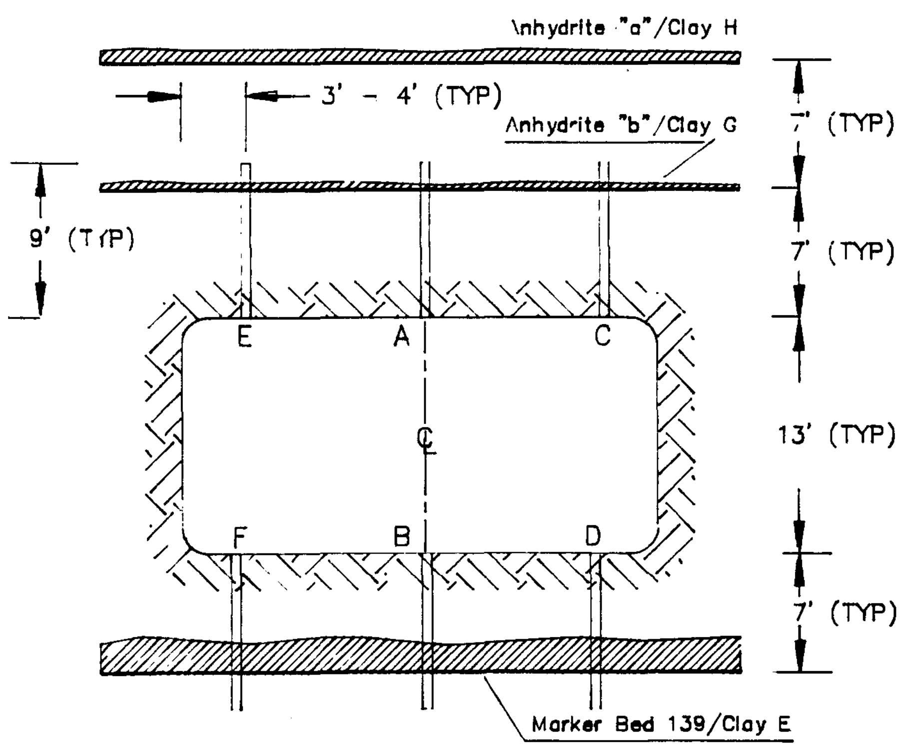

Figure 2. Stratigraphy Around Underground Openings At WIPP

polyhalite occur within the Salado, locally denoted as marker bands.

The facility horizon lies within a 12 meter (40 feet) thick unit of halite, argillaceous halite, and polyhalitic halite, intercalated with thinner beds of anhydrite (Figure 2). The anhydrite beds and associated clay seams are the most structurally important units. Marker Bed 139, a laterally persistent bed of anhydrite, lies about two meters (five feet) below the floor in most areas of the facility, and is underlain by clay E. Anhydrite "a" occurs about four meters (13 feet) above the roof in most excavations. Anhydrite "b" occurs about two meters (seven feet) above the roof.

Marker Bed 139 and the clay layers can have a significant impact on the geomechanical performance of excavations. The clay layers provide surfaces along which slip can occur, whereas Marker Bed 139 acts as a strong, brittle unit that does not deform plastically with time. Undulations along its top resist shear movement along the interface with the overlying salt.

2.0 STRUCTURAL EVALUATION OF EXCAVATIONS

In order to determine if the underground excavations are meeting design criteria and safety standards, the openings are regularly inspected and monitored in a variety of ways.

2.1 Geomechanical Instrumentation System

Hundreds of geomechanical instruments have been installed in the underground excavations at WIPP. Multiple point borehole extensometers (MPBX) and various convergence measuring instruments are the primary devices, although inclinometers, stress meters, crack meters, time domain reflectometry cables, and rockbolt load cells have also been used. These instruments are read on a regular basis and provide information on the performance of the excavations. Increasing rates of displacement generally indicate the development of instability in the rock surrounding the excavations. MPBX's provide indirect information on displacements of fractures and separations at stratigraphic contacts.

2.2 Visual Inspections

The simplest methods of monitoring excavation conditions are visual. The conditions of the roof, floor, and walls of the excavations are regularly assessed at WIPP. Areas of spalling and heave are noted and compared to earlier inspections to determine how quickly conditions are changing. The type and extent of ground control installed in an area is also noted. This qualitative method primarily serves to locate areas of concern which may require more detailed analysis.

2.3 Geophysical Methods

Several geophysical methods have been employed at WIPP to determine structural conditions. Ground probing radar has been successfully used to delineate large fractures and clay seams within a few meters of the excavation surfaces. Radar is the only reliable way to observe the condition of the rock without drilling boreholes. However, this method is very expensive, requiring special equipment and training for personnel and is very labor intensive in terms of both fieldwork and data reduction and analysis. In addition, this method does not reveal small fractures which may be as important structurally as the larger fractures it is capable of discerning.

Resistivity methods have been used at WIPP with limited success. Resistivity is not capable of discerning individual fractures. There is also a good deal of ambiguity in resistivity results, as both the competence of the rock and the amount of water in the rock mass effect the resistivity of the ground. Like radar, resistivity requires an investment in specialized equipment and is labor intensive. At this time, resistivity is of only academic interest and does not give practical results.

2.4 Borehole Inspections

Borehole inspections have been the most successful method for determining the condition of the rock immediately surrounding excavations. Fracture logging of open boreholes has been done on an informal basis since the first holes were drilled at the facility horizon in 1983. Concern over the extent and nature of fracturing near excavations increased in 1985 when a well developed fracture system was discovered in the floor of SPDV Test Room 3, also called Room T. This fracturing spanned the room from rib to rib and extended into the thick anhydrite Marker Bed 139 (MB-139). Open spaces across fractures as great as 15 cm (six inches) were observed. This activity heightened interest in fracturing at WIPP and lead to the establishment of the Excavation Effects Program (EEP) in the following year.

3.0 EXCAVATION EFFECTS PROGRAM

The Excavation Effects Program (EEP) was initiated shortly after the discovery of the large fracture system in SPDV Test Room 3.

The purpose of the Excavation Effects Program is to study fracture development as a result of underground excavations at the WIPP. As part of the Geotechnical Monitoring Program, the EEP was developed to provide consistent documentation and monitoring of fracture development. The program was begun in 1986 to meet these needs.

The EEP utilizes the inspection of drill holes in the excavations to provide information on the extent of fracturing and development. These data are compared with instrument data to provide an understanding of the geomechanical performance of the rock.

The Excavation Effects Program is intended to:

1. determine the extent of subsurface fracturing around underground excavations at WIPP,
2. establish a systematic, consistent method for documenting fracture development,
3. provide for further monitoring of fracture development.

The EEP is systematic in that boreholes were drilled in similar patterns at strategic locations. These holes were logged during yearly surveys since 1986. Since then, the Excavation Effects Program has exceeded all expectations in terms of the quantity and the quality of the data collected.

3.1 Methodology

The EEP consisted of drilling 156 48 mm (1-7/8 inch) and 76 mm (three inch) diameter jackleg drill holes at 30 locations (hereafter referred to as arrays) in the SPDV Test Rooms and along selected drifts and intersections (Figure 1). Holes were drilled a nominal 2.75 meters (nine feet) into the roof and floor at most of the arrays. A typical array layout is shown in Figure 1. The 2.75 meter depth was chosen because it would penetrate the first major clay seam in both the roof and floor in most locations. Economics and limitations of the drilling method were also factors.

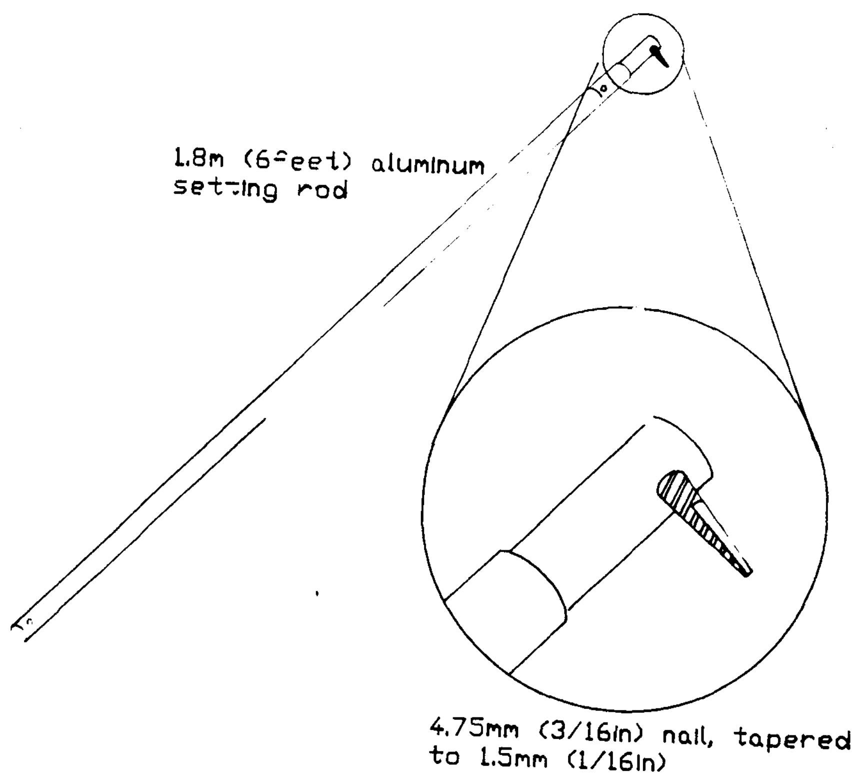

Figure 3. Excavation Effects Program Probe

3.1.1 Mapping Procedure

The arrangement of the boreholes in each array was chosen to intercept locations in the roof and floor which were thought to be more likely to have fracturing. In some instances, pre-existing boreholes were utilized when they were close enough to the desired locations to make drilling a new hole unnecessary. The centerline holes at most arrays were drilled with a 76 mm (three inch) diameter to facilitate inspections with a borehole camera if necessary.

All holes were inspected using an aluminum probe rod with a flattened nail or screw about 1.5 mm (1/16 inch) wide attached normal to one end (Figure 3). Features were identified by scratching the nail along the sides of the borehole while applying moderate pressure. Features were located when the nail caught on the borehole wall at the same depth on all sides of the wall.

For the purposes of this program, a fracture is defined as any discontinuity with a mappable vertical or horizontal component of displacement. Vertical displacement across features was measured by the length of the nail penetration for separations less than about 4.75 mm (3/16 inch). This was possible because the nail was ground from 1.5 mm (1/16 inch) at the tip to 4.75 mm (3/16 inch) at the base. Vertical displacements greater than 4.75 mm (3/16 inch) were determined by the amount of vertical rod movement within the feature. Horizontal displacement magnitude was visually estimated when possible. When visual estimation was not possible, the magnitude was estimated by feel (with the rod). Places where the nail caught on the borehole wall but did not penetrate the wall along most of its perimeter were designated "hang ups" and were considered to be possible fractures.

3.2 Results

The results of six years of EEP borehole observations will now be summarized.

3.2.1 Fracture Patterns

One of the greatest insights from the EEP data is the fact that regardless of the size or stratigraphic location of an excavation, the fracture pattern in the roof and floor of the excavation is very similar. This allowed us to design a roofbolt pattern that not only addresses the fracture pattern but is universally applicable throughout the mine, regardless of the drift width.

A schematic depicting the typical fracture pattern found in the roof and floor of excavations at WIPP is shown in Figure 4. Diagonal fractures tend to develop near the rib-roof intersection which in the extreme cases, terminate at the clay seam about two meters into the back. In the more advanced cases, subhorizontal fractures begin to develop near the centerline of the excavation just below clay G. Subhorizontal spalls also develop within the first few centimeters of the excavation surfaces.

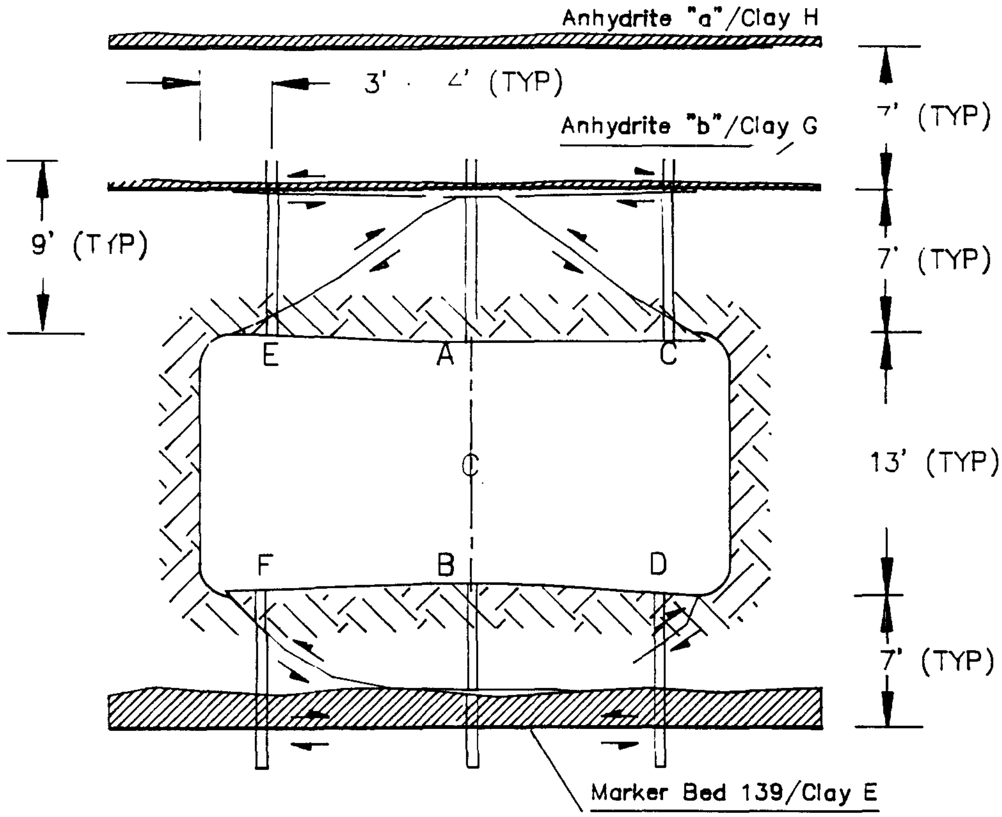

Figure 4. Typical Deformation Patterns Around Underground Opening At WIPP

In the floor, the dish-shaped fractures first seen in SPDV Test Room 3 are prevalent throughout the mine.

3.2.2 Stratigraphic Offsetting

The EEP borehole observations have shown us that significant horizontal offsets develop at clay seams near excavations. In most cases, the beds nearer to the excavation move towards the centerline of the excavation relative to the deeper beds. The offsetting is usually symmetrical around the centerline of the room, with the greatest offset magnitude near the ribs (Figure 4). The rate of offset of the beds has been determined from the EEP observations to range from about 3 to 12.5 mm/year (1/8 to 1/2 inch/year), about 3 mm/year (1/8 inch) on average. As will be seen later, this is very important to the design of roof bolt systems that penetrate the clay seams. Speculation on the cause of the bed offsetting is discussed in Section 4.

3.2.3 Development with Time

Information concerning the rate of development of fractures and the effect of drift size on the rate was obtained from EEP observations. The EEP data indicated that the rate of fracture development was much greater than generally assumed. However, there appears to be no direct relationship between excavation age and fracture frequency. Comparison of the ages of individual locations (time since excavation) with fracturing yields very inconsistent results. Very young excavations sometimes have more fracturing than very old ones. Since few of the excavations were mined at the same time (say within a month), the data set size for a given age of excavation is frequently unity and any ensuing statistical analyses are, of course, meaningless. Grouping the ages to increase the set size proves very difficult and is difficult to justify. However, when the age of the entire data set is considered rather than that of individual locations, a relationship between age and fracturing becomes evident. Figure 5 contains plots of drift span versus fracturing for each of the first four surveys. After 1989, nearly all arrays had fracturing or were inaccessible, so the data for 1990 to 1992 are not included in this analysis. It is clear that the lines for successive years are shifted up each year. The increase is not consistent in magnitude, but one must consider the fact that age of excavation indirectly influences fracture development (or has a direct influence that is of less importance than drift span). Figure 5 can, with caution, be used to predict the likelihood of fracture development in a drift of given span and age. Using this plot for predictions is questionable for locations not included in the original surveys, for locations of more complex geometry, or for locations which were included in the original survey but have since been altered (in terms of geometry). It almost certainly is only applicable to the mine from which the data was collected.

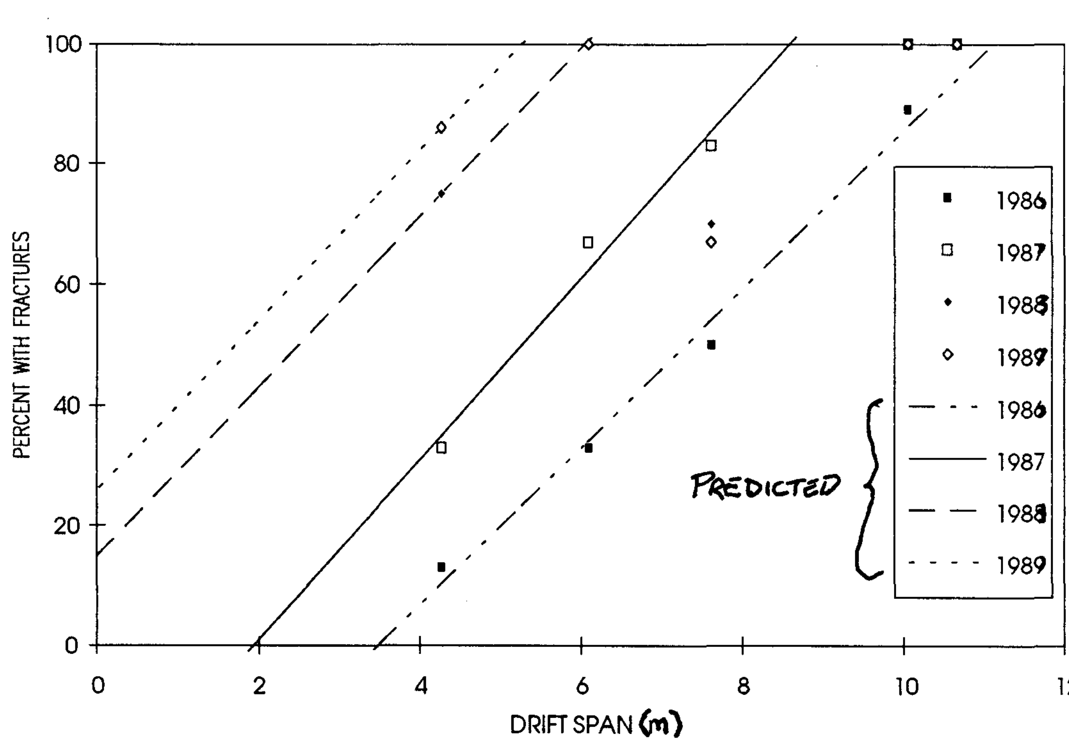

Figure 5: Drift Span Versus Fracture Frequency

3.2.4 Excavation Geometry

The geometry or dimensions (height X width) of an excavation appear to have some influence on the occurrence and intensity of fracturing, as shown by the plots in Figure 5. The x-axis is the span or width of the drift where the array is located. The y-axis is the percent of arrays of a certain span for which fracturing was observed in at least one borehole. There appears to be a linear relationship between fracturing and drift span.

The problem with this analysis is that the data set is not well distributed across the range of drift spans. For example, one third of all arrays have 10 meter (33 feet) spans while only one tenth have 6 meter (20 feet) spans. Therefore, one must consider the number of arrays with a particular span when using Figure 5. Despite the statistical questionability, one must conclude that drift span has an influence on fracture development.

When analyzed in the same manner as drift span, there appears to be no correlation between drift height or cross-section with fracture frequency.

3.2.5 Correlation with Instrument Data

Convergence data can suggest the location and extent of fractures. Convergence instruments have shown that the deformation across the width of the drift is rarely uniform. In many cases, one side of a drift shows significantly higher convergence rates than the other. Frequently, there is greater fracturing on the side with higher convergence rates.

Multiple point borehole extensometers are perhaps more efficient at detecting fractures. In the SPDV Test Rooms, the development of large separations at clay seams was first detected through extensometer readings and confirmed through EEP borehole inspections.

4.0 CONCEPTUAL MODEL FOR EXCAVATION EFFECTS

The stratigraphy immediately above the Test Rooms (and the waste storage panels) typically comprises two layers of halite, each about two meters (seven feet) thick, with a thin anhydrite bed and clay seam above each layer (Figure 4). The clay seams have virtually no structural competence, thus the two halite layers can be considered as separately acting beams. The observations of offsetting at clay G from the Excavation Effects Program inspections and the unusually high strains across clay G seen in the MPBX analyses confirm this.

The compression of the pillars imposes horizontal compressive forces to the roof and floor beams above and below the excavation. This force, the vertical loads imparted by the overlying material, and the self-weight of the beams cause the beams to deflect downward, more so towards the center of the beams. The greater the horizontal movement of the ribs, the larger the drift span, and the smaller the flexural rigidity of the beam, the greater the deflection of the beam. Separation between the beams is the result of one beam deflecting more than the other. Because the lower beam has undergone more displacement, it can be assumed that the lower halite layer has been subjected to more strain than the upper layer. It can further be assumed that the lower beam has less flexural rigidity than the upper layer due to the greater structural weakening caused by the greater strain and the lack of confinement. This bending would lead to horizontal displacement near the ends and vertical displacement near the center of the contact between layers (Figure 4). This pattern is frequently observed in the EEP borehole arrays.

Although the beam ends probably displace both vertically and horizontally, it is assumed that the vertical movement of one end relative to the other is negligible since the magnitudes of vertical creep of ribs on opposite sides of an opening are nearly equal.

The lower beam is apparently being carried towards the room along with the ribs as the ribs creep inward. The rates of horizontal displacement at clay G derived from the EEP surveys are equal to 75% or more of the horizontal displacements of the surfaces of the ribs. The lower beam being deflected by creep of the ribs in addition to its own weight and the weight of the overlying beam would account for the increasing separation at the clay seam seen in the bay strains from roof extensometers

The beam deflection/buckling theory accounts for much of the EEP and instrumental observation. However, there are certainly other forces at work which involve changes to the material properties of the halite. Fracturing in halite, rather than creep, is induced by strain rates exceeding a critical value for a given temperature and stress situation. It can be assumed that there exists a zone immediately surrounding all excavations which is practically de-stressed or stress relieved. In this zone, it must also be assumed that strain rates remain relatively high due to the continued movements of the rock farther from the opening where stress levels are appropriate for creep. It is therefore inevitable that strain rates near the surfaces of the excavation will exceed the level required for fracturing to develop. This causes spalling and similar phenomenon seen so often on the surfaces of the drifts.

5.0 APPLICATION OF RESULTS

The Excavation Effects Program borehole surveys have significantly advanced our understanding of the deformation mechanisms and the development of fractures surrounding the underground excavations at WIPP. Several practical applications of this knowledge have improved operations at WIPP.

5.1 SPDV Test Room 1 Roof Fall

The Site and Preliminary Design Validation Test Rooms in the north end of the repository were excavated to monitor the closure, fracture development, and rock behavior in the underground. The information gathered from the test rooms enable design modifications to enhance the life of the rooms in the waste storage panel.

Observations in these rooms, including Excavation Effects Program data, have been made over the past eight years. Low angled shear fractures had, with time, formed in the roof of Test Room 1 and propagated along the length of the room. In addition, a separation occurred at the base of anhydrite "b", approximately seven feet above the roof. This led to the formation of an arch-shaped slab up to two meters (6.9 feet) in the center which separated from the overlying salt along the fractures and at anhydrite "b". On February 4, 1991, an arch-shaped section of roof weighing approximately 6.2 MN (700 tons) separated from the overlying salt and fell into the room. The section of rock which fell measured approximately 43 meters (140 feet) in length, ten meters (33 feet) in width, and has a maximum thickness of about two meters (seven feet).

The development of the roof failure was closely monitored. Indications of roof instability were observed in the Excavation Effects Program data approximately five years before the roof fall, and in instrument data from SPDV Test Room 1 approximately three years before the roof fall. An extensive program to map the fractures and upgrade the instrumentation in the Test Rooms was initiated. Analysis of the data resulted in the timely abandonment of the room. Remotely read instrumentation allowed convergence measurements to be made to within ten minutes of the roof fall. The geomechanical data from this room provided a unique study of roof behavior above an excavation in bedded salt from its construction until immediately preceding a large failure. Test Room 1 provides the most detailed example of the performance that can be expected from other rooms having similar geometries.

5.2 Roof Support Systems

The roof support systems used at WIPP were designed to address the fracture patterns revealed by the EEP borehole observations. The EEP-influenced designs saved labor and material costs that would have been incurred by constructing more conservative roof support systems which would have been required without the knowledge gained from the EEP.

5.2.2 General Mine Rockbolt Pattern

Before the first underground openings were excavated at WIPP, it was thought that rockbolting would only be required for remediation of isolated sections of bad ground. However, the EEP borehole observations made it clear that large scale fracturing of the roof of the excavations was likely throughout the mine. Therefore, a rockbolt pattern was devised to specifically address the fracture patterns observed in the EEP.

The general rockbolt pattern used in

most of the mine is divided into three sections (Figure 6). The center third of the drift uses three meter bolts on a 1.2 X 1.2 meter offsetting square pattern. The outer two thirds are on an 1.2 X 1.8 meter pattern. The rockbolt pattern was designed to support a triangular slab with a height of two meters and a ten meter base. The concentration of the support is at the center of the drift cross-section because, according to Excavation Effects Program data, the thickest part of the roof slab is in the middle. The intent of the rockbolt design was not to beam-build but to simply support the dead weight of the slab predicted by the EEP data.

This pattern has been installed in all accessible drifts in the mine and has performed well for short term support. However, as the installations aged, the frequency of failures of rockbolts has increased. Many bolts have failed at the level of clay G. Apparently, the horizontal offsetting at the clay seam imparts an axial load to the bolt, causing tensile failure. To date, this has happened to only a very small percentage of the installed rockbolts.

5.2.3 Panel 1, Room 1, Rockbolt Pattern

The environmentally sensitive mission of WIPP places requirements on mine operations that are not normally encountered in mining. The design of the roof support system for Panel 1, Room 1, the first room scheduled for receiving transuranic waste experiments, was subjected to intense scrutiny. It was determined by external

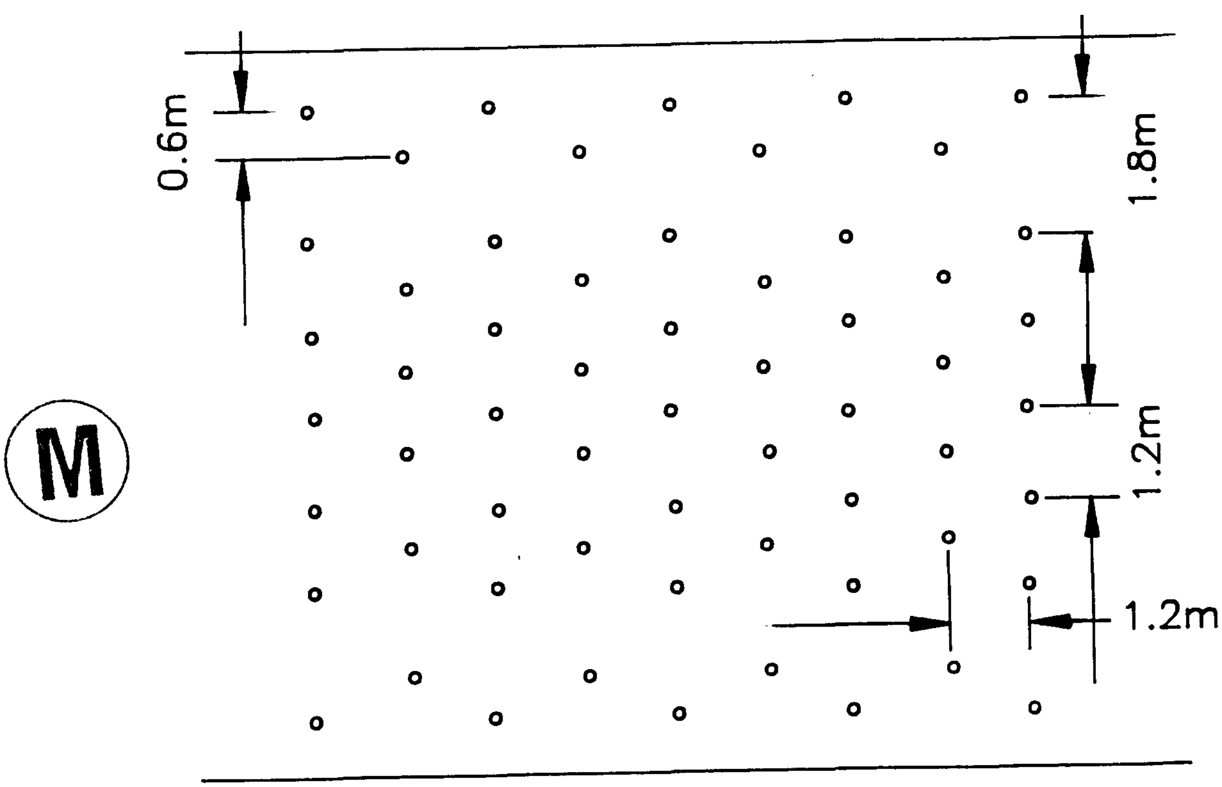

Figure 6. General Mine Rockbolt Layout

organizations that the support system in this room must guarantee stability for the duration of the waste experiments (U.S. DOE, 1991). This would mean the room would be at least twelve years old at the time the experiments were scheduled to terminate. Unfortunately, the roof fall discussed earlier occurred in a similar room less than eight years after its excavation. Therefore, an extremely conservative support design was required.

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6.0 CONCLUSIONS

The experience with borehole fracture observations and their applications gained from the Excavation Effects Program at the Waste Isolation Pilot Plant has led to the following recommendations and conclusions.

1. A borehole observation program must use arrays of boreholes with consistent layouts in order to provide statistically meaningful results.

2. Because borehole observations are frequently subjective, the best data is obtained when the same person completes each survey.

3. Boreholes destroyed by mining should be replaced immediately to allow continuity of data.

4. The EEP is an inexpensive, fast method for determining the condition of the ground surrounding underground excavations.

5. The EEP provides information necessary to efficiently design a roof support system in bedded rock.

6. The EEP enabled the project to predict the size and shape of a large roof fall, and in combination with instrument analyses, formed the basis for an accurate prediction of the time of the roof fall.

REFERENCES

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The Excavation Effects Program at the Waste Isolation Pilot Plant

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ABSTRACT: Excavation effects are the observable evidence of damage incurred by the rock mass due to the removal of material during mining. Excavation effects of primary concern to ground control and maintenance engineers are the displacement of the rock and the formation of various types of fractures and separations near the excavation. Well established and relatively simple techniques already exist for measuring rock displacements. Characterization of fracture systems surrounding excavations is a much more difficult problem, especially in creeping materials such as halite for which the extent and orientation of fracturing may change continually with time. Many indirect geophysical methods, such as ground probing radar, are available for this purpose, but they are usually quite costly and require equipment and expertise normally not available at a production mine.

An inexpensive technique developed for characterizing fracture systems surrounding underground excavations at the Waste Isolation Pilot Plant (WIPP) provides a quick and systematic method that does not require special expertise to use successfully. WIPP is being developed near Carlsbad, New Mexico, for the disposal of transuranic nuclear wastes in underground excavations in salt 2150 feet below the surface.

1 INTRODUCTION

Ground control is a basic, fundamental problem that must be considered by every underground operation. The magnitude of ground control problems at a facility directly affects production rates, operational costs, facility design, engineering effort, and operational safety. Underground operations in salt at the Waste Isolation Pilot Plant (WIPP) are especially sensitive to ground control concerns where they affect criteria for operational safety and waste retrievability in an ever changing operational environment. Programs were implemented at WIPP to monitor the response of the salt to excavations. The information from these programs is important to the continued safe operation of the plant, as well as to the mining industry as a whole.

1.1 *Waste Isolation Pilot Plant*

The WIPP was authorized by Congress in 1979 (Public Law 96-164) to provide "...a research and development facility to demonstrate the safe disposal of radioactive wastes resulting from the defense activities and programs of the United States exempted from regulation by the Nuclear Regulatory Commission" (U.S. DOE, 1992). The WIPP is intended to receive, handle, and permanently dispose of transuranic waste. To fulfill this mission, the U.S. Department of Energy (DOE) is constructing a full-scale facility to demonstrate both technical and operational principles of the permanent isolation of transuranic waste. The facility is also designed for in-situ studies and experiments in salt.

1.2 *Location*

The WIPP is located in the United States in southeastern New Mexico about 50 km (30 miles) east of Carlsbad. The surface facilities have been built on the flat to gently rolling hills that are characteristic of the Los Medanos (sand hills) area. The underground facilities are being excavated approximately 655 meters (2,150 feet) beneath the surface. Figure 1 shows a plan view of the underground facilities at the WIPP site.

1.3 *Geology*

The WIPP facility excavations are located in the Permian Salado Formation, a thick sequence of bedded evaporite deposits. The formation is composed predominantly of halite containing

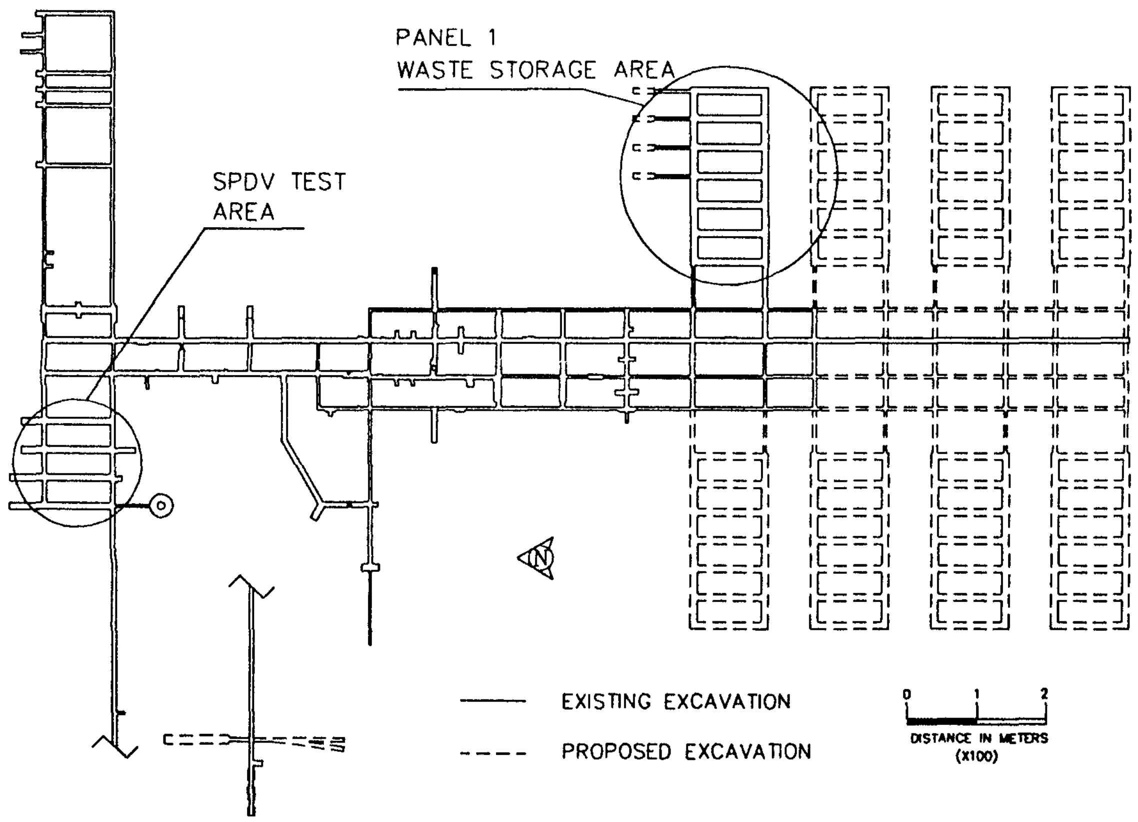

Figure 1. Waste Isolation Pilot Plant (WIPP) Mine Plan

minor amounts of clay, anhydrite, and polyhalite. Several areally persistent layers of anhydrite and polyhalite occur within the Salado, locally denoted as marker beds.

The facility horizon lies within a 12 meter (40 feet) thick unit of halite, argillaceous halite, and polyhalitic halite, intercalated with thinner beds of anhydrite (Figure 2). The anhydrite beds and associated clay seams are the most structurally important units. Marker Bed 139, a persistent bed of anhydrite, lies about two meters (five feet) below the floor in most areas of the facility and is underlain by clay E. Anhydrite "a" occurs about four meters (13 feet) above the roof in most excavations. Anhydrite "b" occurs about two meters (seven feet) above the roof.

Marker Bed 139 and the clay layers can have a significant impact on the geomechanical performance of excavations. The clay layers provide surfaces along which slip can occur, whereas Marker Bed 139 acts as a strong, brittle unit that does not deform plastically with time. Undulations along its top resist shear movement along the interface with the overlying salt.

2 STRUCTURAL EVALUATION OF EXCAVATIONS

In order to determine if the underground excavations are meeting design criteria and safety standards, the openings are regularly inspected and monitored in a variety of ways.

2.1 *Geomechanical Instrumentation System*

Hundreds of geomechanical instruments have been installed in the underground excavations at WIPP. Multiple point borehole extensometers (MPBX) and various convergence measuring instruments are the primary devices, although inclinometers, stress meters, crack meters, time domain reflectometry cables, and rockbolt load cells have also been used. These instruments are read on a regular basis and provide information on the performance of the excavations. Increasing rates of displacement generally indicate the development of instability in the rock surrounding the excavations. MPBX's provide indirect information on displacements of fractures and separations at stratigraphic contacts.

2.2 *Visual Inspections*

The simplest methods of monitoring excavation conditions are visual. The conditions of the roof, floor, and walls of the excavations are regularly assessed at WIPP. Areas of spalling and heave are noted and compared to earlier inspections to determine how quickly conditions are changing. The type and extent of ground control installed in an area is also noted. This qualitative method primarily serves to locate areas of concern which may require more detailed analysis.

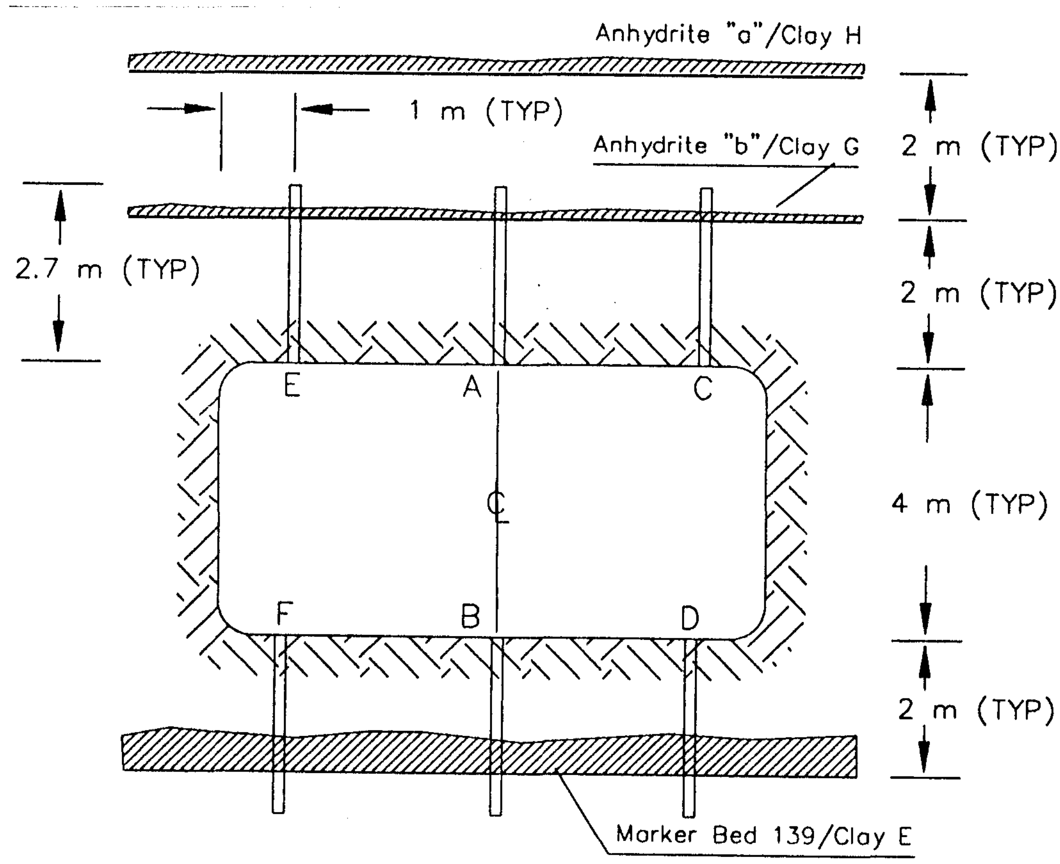

Figure 2. Stratigraphy Around Underground Openings at WIPP

2.3 *Geophysical Methods*

Several geophysical methods have been employed at WIPP to determine structural conditions. Ground probing radar has been successfully used to delineate large fractures and clay seams within a few meters of the excavation surfaces. Radar is the only reliable way to observe the condition of the rock without drilling boreholes. However, this method is very expensive, requiring special equipment and training for personnel and is very labor intensive in terms of both fieldwork and data reduction and analysis. In addition, this method does not reveal small fractures which may be as important structurally as the larger fractures it is capable of discerning.

Resistivity methods have been used at WIPP with limited success. Resistivity is not capable of discerning individual fractures. There is also a good deal of ambiguity in resistivity results, as both the competence of the rock and the amount of water in the rock mass effect the resistivity of the ground. Like radar, resistivity requires an investment in specialized equipment and is labor intensive. At this time, resistivity is of only academic interest and does not give practical results.

2.4 *Borehole Inspections*

Borehole inspections have been the most successful method for determining the condition of the rock immediately surrounding excavations. Fracture logging of open boreholes has been done on an informal basis since the first holes were drilled at the facility horizon in 1983. Concern over the extent and nature of fracturing near excavations increased in 1985 when a well developed fracture system was discovered in the floor of Site and Preliminary Design Validation (SPDV) Test Room 3. This fracturing spanned the room from rib to rib and extended into the thick anhydrite Marker Bed 139 (MB-139). Open spaces across fractures as great as 15 cm (six inches) were observed. This activity heightened interest in fracturing at WIPP and lead to the establishment of the Excavation Effects Program (EEP) in the following year.

3 EXCAVATION EFFECTS PROGRAM

The EEP was initiated shortly after the discovery of the large fracture system in SPDV Test Room 3.

The purpose of the EEP is to study fracture development as a result of underground excavations at the WIPP. As part of the Geotechnical Monitoring Program, the EEP was developed to provide consistent documentation and monitoring of fracture development. The program was begun in 1986 to meet these needs.

The EEP utilizes the inspection of drill holes in the excavations to provide information on the

(M)

extent of fracturing and development. These data are compared with instrument data to provide an understanding of the geomechanical performance of the rock.

The EEP is intended to:

1. determine the extent of subsurface fracturing around underground excavations at WIPP,
2. establish a systematic, consistent method for documenting fracture development,
3. provide for further monitoring of fracture development.

The EEP is systematic in that boreholes were drilled in similar patterns at strategic locations. These holes were logged during yearly surveys since 1986. Since then, the EEP has exceeded all expectations in terms of the quantity and the quality of the data collected.

3.1 *Methodology*

The EEP consisted of drilling 156 48 mm (1-7/8 inch) and 76 mm (three inch) diameter jackleg drill holes at 30 locations (hereafter referred to as arrays) in the SPDV Test Rooms and along selected drifts and intersections. Holes were drilled a nominal 2.75 meters (nine feet) into the roof and floor at most of the arrays. A typical array layout is shown in Figure 2. The 2.75 meter depth was chosen because it would penetrate the first major clay seam in both the roof and floor in most locations. Economics and limitations of the drilling method were also factors.

3.1.1 *Mapping Procedure*

The arrangement of the boreholes in each array was chosen to intercept locations in the roof and floor which were thought to be more likely to have fracturing. In some instances, pre-existing boreholes were utilized when they were close enough to the desired locations to make drilling a new hole unnecessary. The centerline holes at most arrays were drilled with a 76 mm (three inch) diameter to facilitate inspections with a borehole camera if necessary.

All holes were inspected using an aluminum probe rod with a flattened nail or screw about 1.5 mm (1/16 inch) wide attached normal to one end (Figure 3). Features were identified by scratching the nail along the sides of the borehole while applying moderate pressure. Features were located when the nail caught on the borehole wall at the same depth on all sides of the wall.

For the purposes of this program, a fracture is defined as any discontinuity with a mappable vertical or horizontal component of displacement. Vertical displacement across features was measured by the length of the nail penetration for separations less than about 4.75 mm (3/16 inch). This was possible because the nail was ground from 1.5 mm (1/16 inch) at the tip to 4.75 mm (3/16 inch) at the base. Vertical displacements greater than 4.75 mm (3/16 inch) were determined by the amount of vertical rod movement within the feature. Horizontal displacement magnitude was visually estimated when possible. When visual estimation was not possible, the magnitude was estimated by feel (with the rod). Places where the nail caught on the borehole wall but did not penetrate the wall along most of its perimeter were designated "hang ups" and were considered to be possible fractures.

3.2 *Results*

The results of six years of EEP borehole observations will now be summarized.

3.2.1 *Fracture Patterns*

One of the greatest insights from the EEP data is the fact that regardless of the size or stratigraphic location of an excavation, the fracture pattern in the roof and floor of the excavation is very similar. This allowed us to design a roof-bolt pattern that not only addresses the fracture pattern but is universally applicable throughout the mine, regardless of the drift width.

A schematic depicting the typical fracture pattern found in the roof and floor of excavations at WIPP is shown in Figure 4. Diagonal fractures tend to develop near the rib-roof intersection which, in the extreme cases, terminate at the clay seam about two meters into the back. In the more advanced cases, subhorizontal fractures begin to develop near the centerline of the excavation just below clay G. Subhorizontal spalls also develop within the first few centimeters of the excavation surfaces.

In the floor, the dish-shaped fractures first seen in SPDV Test Room 3 are prevalent throughout the mine.

3.2.2 *Stratigraphic Offsetting*

The EEP borehole observations have shown us that significant horizontal offsets develop at clay seams near excavations. In most cases, the beds nearer to the excavation move towards the centerline of the excavation relative to the deeper beds. The offsetting is usually symmetrical around the centerline of the room, with the greatest offset magnitude near the ribs (Figure 4). The rate of offset of the beds has been determined from the EEP observations to range from about 3 to 12.5 mm/year (1/8 to 1/2 inch/year), about 3 mm/year (1/8 inch) on aver-

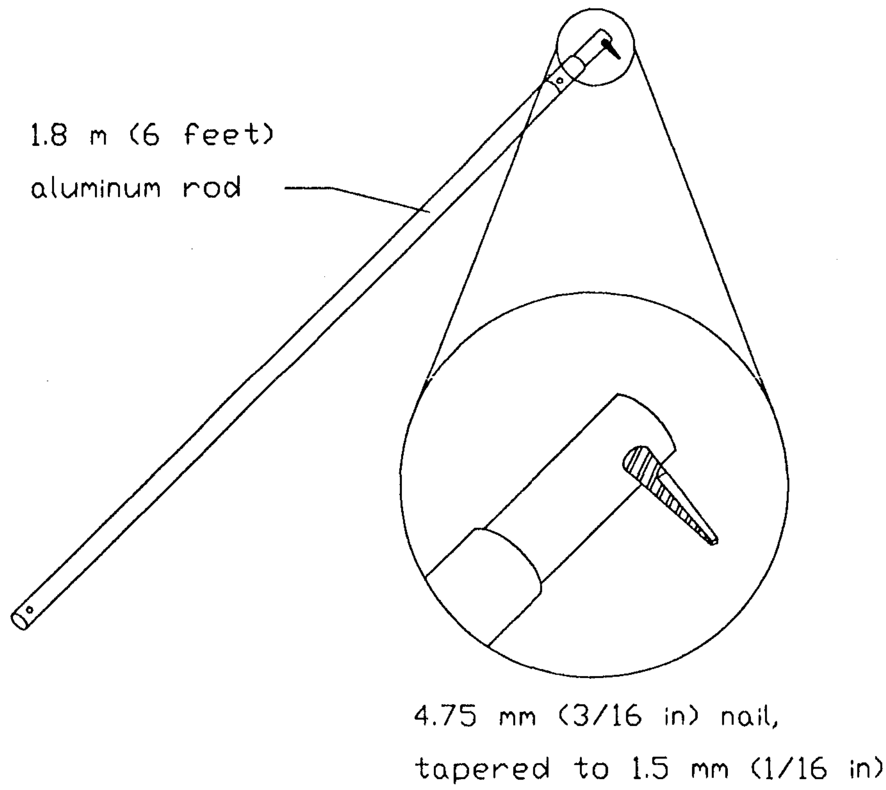

Figure 3. Excavation Effects Program Probe

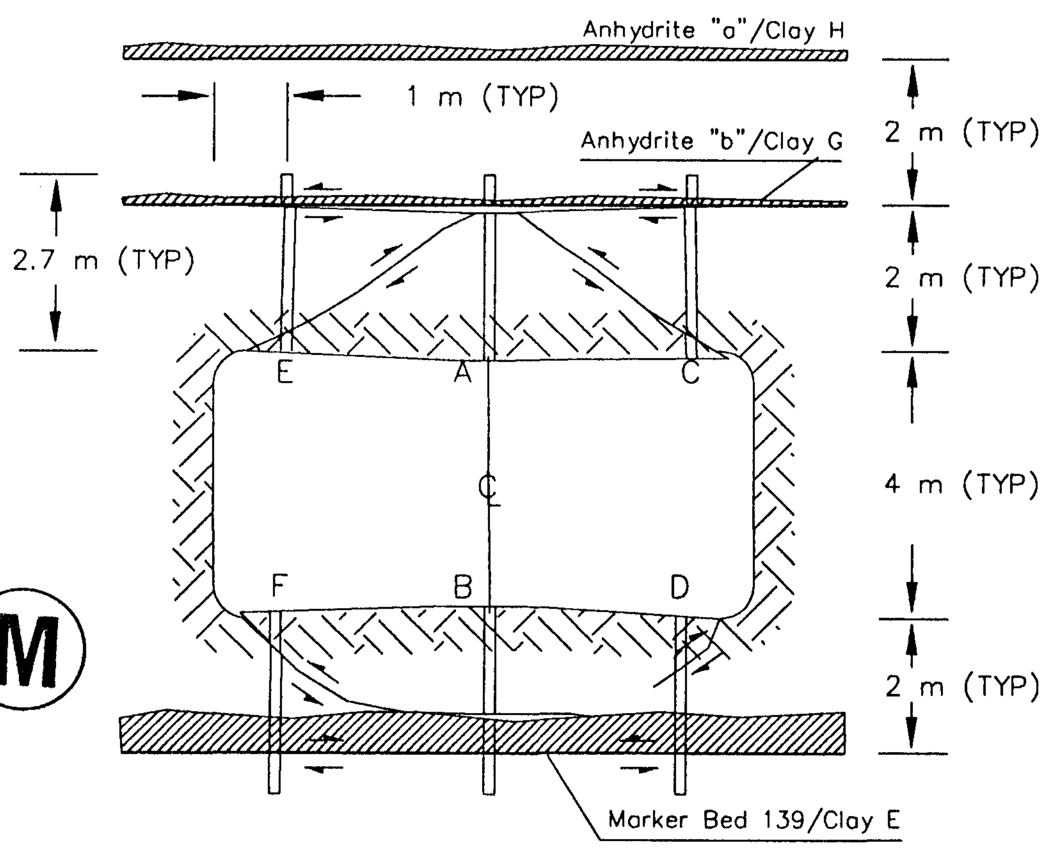

Figure 4. Typical Deformation Patterns Around Underground Openings at WIPP

age. As will be seen later, this is very important to the design of roof bolt systems that penetrate the clay seams. Speculation on the cause of the bed offsetting is discussed in Section 4.

3.2.3 *Development with Time*

Information concerning the rate of development of fractures and the effect of drift size on the rate was obtained from EEP observations. The EEP data indicated that the rate of fracture development was much greater than generally assumed. However, there appears to be no direct relationship between excavation age and fracture frequency. Comparison of the ages of individual locations (time since excavation) with fracturing yields very inconsistent results. Very young excavations sometimes have more fracturing than very old ones. Since few of the excavations were mined at the same time (say within a month), the data set size for a given age of excavation is frequently unity and any ensuing statistical analyses are, of course, meaningless. Grouping the ages to increase the set size proves very difficult and is difficult to justify. However, when the age of the entire data set is considered rather than that of individual locations, a relationship between age and fracturing becomes evident. Figure 5 contains plots of drift span versus fracturing for each of the first four surveys. After 1989, fracturing was found at nearly all borehole locations or the holes were inaccessible, so the data for 1990 to 1992 are not included in this analysis. It is clear that the lines for successive years are shifted up each year. The increase is not consistent in magnitude, but one must consider the fact that age of excavation indirectly influences fracture development (or has a direct influence that is of less importance than drift span). Figure 5 can, with caution, be used to predict the likelihood of fracture development in a drift of given span and age. Using this plot for predictions is questionable for locations not included in the original surveys, for locations of more complex geometry, or for locations which were included in the original survey but have since been altered (in terms of geometry). It almost certainly is only applicable to the mine from which the data was collected.

3.2.4 *Excavation Geometry*

The geometry or dimensions (height X width) of an excavation appear to have some influence on the occurrence and intensity of fracturing, as shown by the plots in Figure 5. The x-axis is the span or width of the drift where the array is located. The y-axis is the percent of arrays of a certain span for which fracturing was observed in at least one borehole. There appears to be a linear relationship between fracturing and drift span.

The problem with this analysis is that the data set is not well distributed across the range of drift spans. For example, one third of all arrays have 10 meter (33 feet) spans while only one tenth have 6 meter (20 feet) spans. Therefore, one must consider the number of arrays with a particular span when using Figure 5. Despite the statistical questionability, one must conclude that drift span has an influence on fracture development.

When analyzed in the same manner as drift span, there appears to be no correlation between drift height or cross-section with fracture frequency.

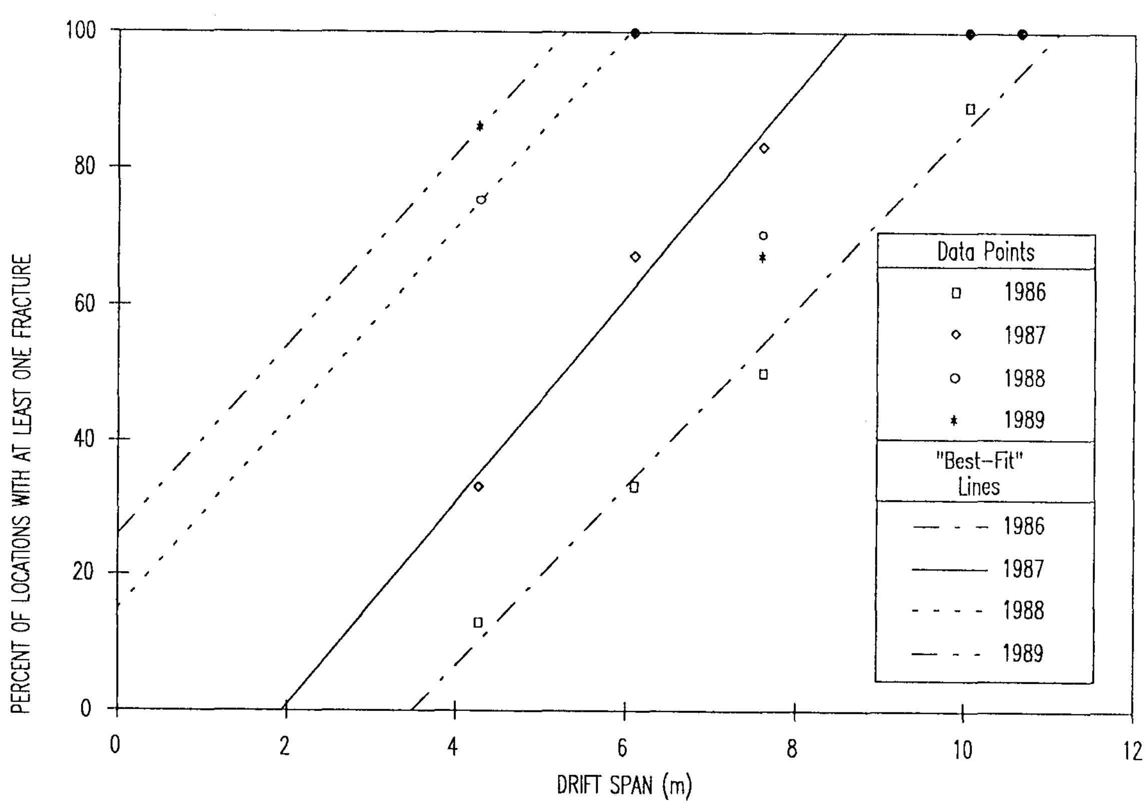

Figure 5. Drift Span Versus Fracturing

3.2.5 *Correlation with Instrument Data*

Convergence data can suggest the location and extent of fractures. Convergence instruments have shown that the deformation across the width of the drift is rarely uniform. In many cases, one side of a drift shows significantly higher convergence rates than the other. Frequently, there is greater fracturing on the side with higher convergence rates.

Multiple point borehole extensometers are perhaps more efficient at detecting fractures. In the SPDV Test Rooms, the development of large separations at clay seams was first detected through extensometer readings and confirmed through EEP borehole inspections.

4 CONCEPTUAL MODEL FOR EXCAVATION EFFECTS

The stratigraphy immediately above the Test Rooms (and the waste storage panels) typically comprises two layers of halite, each about two meters (seven feet) thick, with a thin anhydrite bed and clay seam above each layer (Figure 4). The clay seams have virtually no structural competence, thus the two halite layers can be considered as separately acting beams. The observations of offsetting at clay G from the Excavation Effects Program inspections and the unusually high strains across clay G seen in the MPBX analyses confirm this.

The compression of the pillars imposes horizontal compressive forces to the roof and floor beams above and below the excavation. This force, the vertical loads imparted by the overlying material, and the self-weight of the beams cause the beams to deflect downward, more so towards the center of the beams. The greater the horizontal movement of the ribs, the larger the drift span, and the smaller the flexural rigidity of the beam, the greater the deflection of the beam. Separation between the beams is the result of one beam deflecting more than the other. Because the lower beam has undergone more displacement, it can be assumed that the lower halite layer has been subjected to more strain than the upper layer. It can further be assumed that the lower beam has less flexural rigidity than the upper layer due to the greater structural weakening caused by the greater strain and the lack of confinement. This bending would lead to horizontal displacement near the ends and vertical displacement near the center of the contact between layers (Figure 4). This pattern is frequently observed in the EEP borehole arrays.

Although the beam ends probably displace both vertically and horizontally, it is assumed that the vertical movement of one end relative to the other is negligible since the magnitudes of vertical creep of ribs on opposite sides of an opening are nearly equal.

The lower beam is apparently being carried towards the room along with the ribs as the ribs creep inward. The rates of horizontal displacement at clay G derived from the EEP surveys are equal to 75% or more of the horizontal displacements of the surfaces of the ribs. The lower beam being deflected by creep of the ribs in addition to its own weight and the weight of the overlying beam would account for the increasing separation at the clay seam seen in the bay strains from roof extensometers

The beam deflection/buckling theory accounts for much of the EEP and instrumental observation. However, there are certainly other forces at work which involve changes to the material properties of the halite. Fracturing in halite, rather than creep, is induced by strain rates exceeding a critical value for a given temperature and stress situation. It can be assumed that there exists a zone immediately surrounding all excavations which is practically de-stressed or stress relieved. In this zone, it must also be assumed that strain rates remain relatively high due to the continued movements of the rock farther from the opening where stress levels are appropriate for creep. It is therefore inevitable that strain rates near the surfaces of the excavation will exceed the level required for fracturing to develop. This causes spalling and similar phenomenon seen so often on the surfaces of the drifts.

5 APPLICATION OF RESULTS

The EEP borehole surveys have significantly advanced our understanding of the deformation mechanisms and the development of fractures surrounding the underground excavations at WIPP. Several practical applications of this knowledge have improved operations at WIPP.

5.1 *SPDV Test Room 1 Roof Fall*

The SPDV Test Rooms in the north end of the repository were excavated to monitor the closure, fracture development, and rock behavior in the underground. The information gathered from the test rooms enable design modifications to enhance the life of the rooms in the waste storage panel.

Observations in these rooms, including EEP data, have been made over the past eight years. Low angled shear fractures had, with time, formed in the roof of Test Room 1 and propagated along the length of the room. In addition, a separation occurred at the base of anhydrite "b", approximately seven feet above the roof. This led to the formation of an arch-shaped slab up to two meters thick (6.9 feet) in the center which separated from the overlying salt along the fractures and at anhydrite "b". On February 4, 1991, an arch-shaped section of roof weighing approximately 6.2 MN (700 tons) separated from the overlying salt and fell into the room. The section of rock which fell measured approximately 43 meters (140 feet) in length, ten meters (33 feet) in width, and has a maximum thickness of about two meters (seven feet).

The development of the roof failure was closely monitored. Indications of roof instability were observed in the EEP data approximately five years before the roof fall, and in instrument data from SPDV Test Room 1 approximately three years before the roof fall. An extensive program to map the fractures and upgrade the instrumentation in the Test Rooms was initiated. Analysis of the data resulted in the timely abandonment of the room. Remotely read instrumentation allowed convergence measurements to be made to within ten minutes of the roof fall. The geomechanical data from this room provided a unique study of roof behavior above an excavation in bedded salt from its construction until immediately preceding a large failure. Test Room 1 provides the most detailed example of the performance that can be expected from other rooms having similar geometries.

5.2 *Roof Support Systems*

The roof support systems used at WIPP were designed to address the fracture patterns revealed by the EEP borehole observations. The EEP-influenced designs saved labor and material costs that would have been incurred by constructing more conservative roof support systems which would have been required without the knowledge gained from the EEP.

5.2.2 *General Mine Rockbolt Pattern*

Before the first underground openings were excavated at WIPP, it was thought that rockbolting would only be required for remediation of isolated sections of bad ground. However, the EEP borehole observations made it clear that large scale fracturing of the roof of the excavations was likely throughout the mine. Therefore, a rockbolt pattern was devised to specifically address the fracture patterns observed in the EEP.

The general rockbolt pattern used in most of the mine is divided into three sections (Figure 6). The center third of the drift uses three meter bolts on a 1.2 x 1.2 meter offsetting square pattern. The outer two thirds are on an 1.2 x 1.8 meter pattern. The rockbolt pattern was designed to support a triangular slab with a height of two meters and a ten meter base. The concentration of the support is at the center of the drift cross-section because, according to EEP data, the thickest part of the roof slab is in the middle. The intent of the rockbolt design was not to beam-build but to simply support the dead weight of the slab predicted by the EEP data.

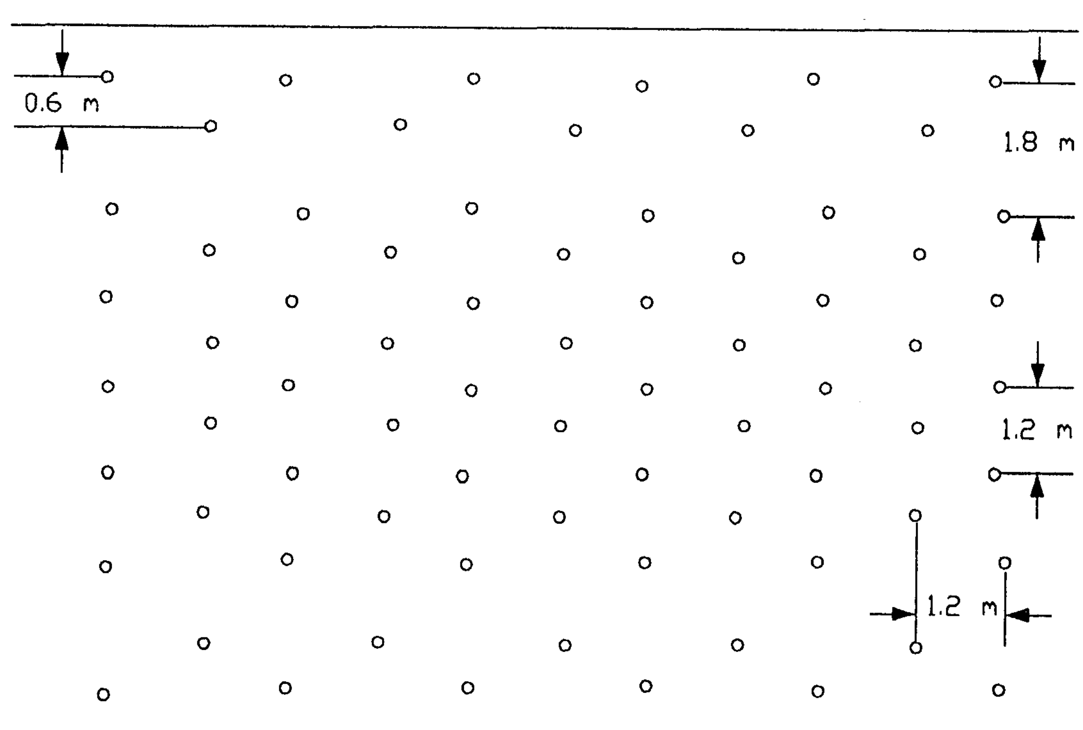

Figure 6. General Mine Rockbolt Layout

This pattern has been installed in all accessible drifts in the mine and has performed well for short term support. However, as the installations aged, the frequency of failures of rockbolts has increased. Many bolts have failed at the level of clay G. Apparently, the horizontal offsetting at the clay seam imparts an axial load to the bolt, causing tensile failure. To date, this has happened to only a very small percentage of the installed rockbolts.

5.2.3 *Panel 1, Room 1, Rockbolt Pattern*

The environmentally sensitive mission of WIPP places requirements on mine operations that are not normally encountered in mining. The design of the roof support system for Panel 1, Room 1, the first room scheduled for receiving transuranic waste experiments, was subjected to intense scrutiny. It was determined by external organizations that the support system in this room must guarantee stability for the duration of the waste experiments (U.S. DOE, 1991). This would mean the room would be at least twelve years old at the time the experiments were scheduled to terminate. Unfortunately, the roof fall discussed earlier occurred in a similar room less than eight years after its excavation. Therefore, an extremely conservative support design was required.

The design of the roof support system in Room 1 was once again influenced by fracture patterns seen in the EEP. This rockbolt design incorporates information concerning the rate of horizontal offsetting of bedding planes, which had been suspected of causing most rockbolt failures at WIPP. The support system consists of the general mine rockbolt pattern using three meter long mechanical anchor bolts, which was installed before the stringent new specifications were developed. A set of four meter (13 feet) long, 25 mm (one inch) diameter Dywidag steel anchor bolts were added to the support system. Once again, the bolts are distributed across the width of the room according to the weight of the slab predicted by the EEP. The bolts are installed on a square pattern with rows (width) about three meters apart. The bolts are 0.61 meters (two feet) apart in the center of the drift, and range from 0.76 meters (2.5 feet) to 0.91 meters (three feet) as the ribs are approached. These bolts have 0.91 meter (three feet) grout anchors. Two types of wire mesh and a set of steel cables running longitudinally along the room were also added to this system. In order to reduce the risk of bolt failure from horizontal offsetting at the clay seam, the ungrouted section of the bolt holes were oversized to 76 mm (3.0 inches) diameter. This is intended to allow horizontal offsetting to occur without impacting the rockbolts.

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