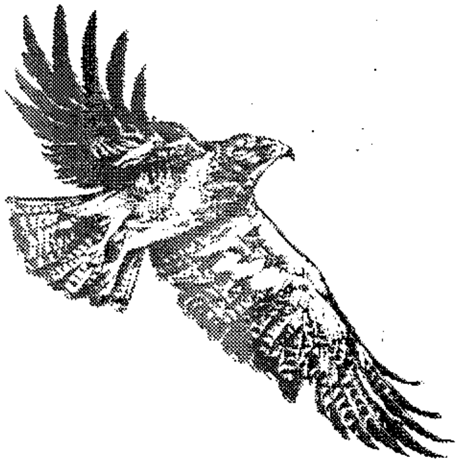
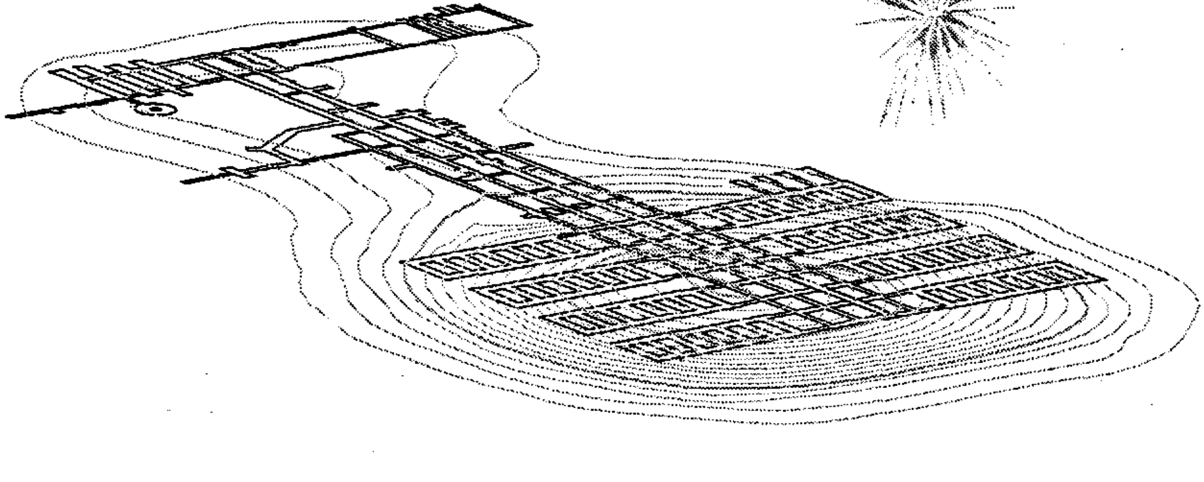


Backfill Engineering Analysis Report



Waste Isolation Pilot Plant

BACKFILL ENGINEERING ANALYSIS REPORT

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Executive Summary

Scope. The Waste Isolation Pilot Plant (WIPP), located in southeastern New Mexico 26 miles east of Carlsbad, is a facility designed for the permanent disposal of transuranic radioactive waste generated at U.S. Department of Energy (DOE) facilities across the United States. The primary purpose of this report is to determine if there is a geomechanical need or advantage to backfilling the WIPP underground. The concept of backfilling the WIPP underground is usually associated with the final sealing of the repository. Since WIPP was designed to be a permanent waste disposal facility, sealing is a part of the decommissioning process, which can include backfilling some or all of the underground workings. The main focus of this report is on the various proposed geomechanical uses for backfill in the WIPP underground; operational and long-term performance uses are also discussed briefly. (Information on the validity of each backfill use is presented, when available.) The primary geomechanical effect explored in this report is subsidence, which could affect the stability of facilities at the surface and in the shafts and could potentially disturb the Culebra Dolomite or other water-bearing units of the Rustler Formation above the WIPP underground facility.

How and Where Backfill Will Be Used at the WIPP. The WIPP underground facilities, excavated 650 meters (m) (2,150 feet [ft]) below the surface in a thick, bedded salt formation, consist of three major areas—the northern experimental area, the waste emplacement area (Panels 1 through 8 to the south—only Panel 1 is presently excavated), and the access drifts located within the "shaft pillar" area between the waste emplacement area and the northern experimental area. Backfill (specifically, backfill containing crushed salt or a combination of crushed salt and additives to enhance the physical and chemical properties of the fill material) could be used in these areas in several ways. Operational uses include placing backfill around waste containers for fire suppression and placing backfill above waste containers to function as a cushion in the event of a roof fall. Long-term performance uses include placing backfill in access drifts as an engineered barrier or sealing material; using backfill as a gas-getter to chemically react with gases that may be generated by the waste; adding backfill in the waste emplacement rooms to adsorb contaminants, to absorb the brine that could flow into rooms from the surrounding rock, and to reduce the disturbed rock zone around drift seal locations; and adding backfill as an intrusion warning marker. Geomechanical uses include using backfill to reduce instability in adjacent openings and to reduce subsidence at the surface and in the overlying strata (specifically the Culebra Dolomite).

Backfill and Subsidence Investigations and Predictions. The use of backfill at the WIPP has been investigated many times. Most of these previous investigations have focused on the chemical and physical properties of different backfill materials and backfill additives. The use of backfill to reduce instability in adjacent openings, however, does not appear to have been previously addressed.

Subsidence predictions for the WIPP site have also been presented in previously published reports. The Final Environmental Impact Statement (FEIS) (DOE, 1980b) provides calculated predictions of the lateral extent of surface subsidence and maximum subsidence. The FEIS calculations indicate that surface subsidence of approximately 0.3 m (1 ft) could be expected with 70 percent backfill (crushed salt backfill placed at a density of 70 percent of intact salt) and approximately 0.5 m (1.6 ft) with 50 percent backfill. Using the equation and assumptions provided in the FEIS, the estimated surface subsidence without backfill would be approximately 1.0 m (3.3 ft).

The Final Safety Analysis Report (DOE, 1990a) predicts an expected maximum surface subsidence of 0.30 to 0.38 m (1 to 1.25 ft) in the shaft pillar area and the waste emplacement area over a period of 35 years. The amount of surface subsidence used for the design of surface structures is based on the amount of creep calculated to occur during the life of the facility and during the compaction of any backfill (the amount and type of which is not indicated). The WIPP Performance Assessment Division at Sandia National Laboratories/New Mexico (SNL/NM) also performed an evaluation of subsidence at the WIPP (SNL/NM, 1991), which predicted the average surface subsidence over the waste emplacement area to be between 0.09 and 0.13 m (0.29 and 0.43 ft) (based on an angle of draw ranging from 35 to 25 degrees, respectively).

For this study, calculational and computer modeling methods were used to help determine the geomechanical effect of backfill on areas within the WIPP underground facility. The mass conservation calculation, the influence function method, and the National Coal Board (NCB) empirical method (NCB, 1975) were used to estimate the amount of subsidence expected from the underground excavations with and without backfill. Subsidence investigations were also performed at potash mining operations located near the WIPP site that have a similar depth and/or stratigraphy. The results of these investigations were used to benchmark the various subsidence prediction methods used in this report.

The mass conservation calculation yielded an estimate of the maximum expected subsidence based on the principle that subsidence is a function of facility dimension and is (therefore) in direct proportion to the seam height and the extraction ratio. The influence function method is based on the assumption that each point in an underground excavation has a circular region of influence on the subsidence at the surface around that point. The NCB method compared the depth and the excavation dimensions at the WIPP to information provided in the NCB tables (NCB, 1975). These tables represent a compilation of data related to specific coal mining situations investigated by the NCB during the period from 1950 to 1965.

In addition to these three methods, a finite difference model (using the Fast Lagrangian Analysis of Continua [FLAC] code) was used to estimate the expected subsidence and interaction of rooms excavated adjacent to one another and the effect of the backfill on each room.

Table ES-1 summarizes the results of the various subsidence prediction models for each of the three WIPP underground areas. The models used several different backfill scenarios that ranged from no backfill at all to a highly compacted crushed salt backfill material placed almost immediately after excavation. These backfilling scenarios provided the end points for the expected range of conceivable backfilling options. The various methods of subsidence prediction provided similar and consistent results. The maximum predicted subsidence over the waste emplacement area, assuming no backfill, ranged from 0.40 to 0.62 m (1.3 to 2.0 ft). Placing backfill material of any kind around the waste drums did not significantly reduce the resulting maximum expected surface subsidence. The maximum predicted surface subsidence with a highly compacted backfill ranged from 0.30 to 0.52 m (1.0 to 1.7 ft). Backfill placement in the waste emplacement area had little effect on the total subsidence, because of the large volume of untreated contact-handled transuranic waste drums (in relation to the crushed salt backfill) and because of the high initial porosity and low stiffness of the waste drums (Butcher and Mendenhall, 1993). Placement of crushed salt backfill in the shaft pillar area and the northern experimental area had a greater relative effect on the reduction of surface subsidence (reducing the total subsidence by more than one half); however, the expected surface subsidence without backfill in these two areas was very small.

Room Interaction. Room interaction was modeled using FLAC. In the models, the drifts were excavated and then backfilled instantaneously at model time zero, although realistically, there would be a time lag of up to five to seven years between excavation and backfilling.

(The backfill effect would probably take much longer under realistic operating schedules.) The results of the modeling indicated that backfill does not significantly affect conditions around an adjacent nonbackfilled drift until 20 model years after excavation. The effect of backfill on stability is dependent on the properties of the backfill and on the rate of backfill consolidation, which is in turn dependent on the convergence rate of the rooms. A delay of seven-plus years between excavation and backfilling would result in significantly longer backfill consolidation times.

Conclusions. Several prediction methods were employed to assess final subsidence above the WIPP repository. These methods represent a cross section of the available prediction techniques existing in published literature—the mass conservation calculation, the NCB empirical method, the influence function method, and a numerical method (finite difference model). The simpler methods of subsidence prediction, such as the NCB method, the influence function method, and the mass conservation method, provided values for surface subsidence similar to those provided by the extensive numerical models. The consistency of the results for these methods provides a high level of confidence in the accuracy of the outcome.

The results of the subsidence modeling indicated that, to improve backfill performance, backfill must be emplaced early in the excavation phase, at the highest achievable density, and minimizing any void spaces such as that between the backfill and the roof of the room. Since some areas of the WIPP underground facilities have been open for over ten years, it will not be possible to fulfill the early emplacement requirement in all cases. Further, based on the FLAC modeling results, there appears to be little difference in the total effect of the backfill on subsidence when different types and porosities of backfill are used, especially in the waste emplacement area, where the subsidence prediction results are heavily dependent on the porosity and the stiffness of the waste. Based on the subsidence predictions, backfill emplacement does not significantly decrease the total subsidence in the waste emplacement area, because of the high initial porosity of the waste, the low stiffness of the waste, and the small amount of backfill relative to the waste volume. If the density or stiffness of the waste were increased prior to placement, through waste treatment such as compaction or solidification (cementation or vitrification), the expected subsidence in the waste emplacement area would decrease.

Total subsidence at the depth of the Culebra Dolomite is expected to be similar to the predicted surface subsidence. Analysis of the FLAC model on horizontal strains at that same depth reveals low and uniform strains up to a maximum strain of 0.007 percent in 380 years. These strains are not expected to cause cracking or extended fracturing, because no faults or discontinuities are known to occur in the WIPP geographic environment and the strain will be uniformly distributed along the strata. Furthermore, the results indicate that subsidence is not expected to cause extensive fracturing that could form a migration path between the underground repository and the Culebra Dolomite or other overlying units.

Predicted horizontal strains at the surface and at the shaft and any tilt associated with the shaft are far below NCB guidelines for such structures (NCB, 1975). Consequently, no structural or operational problems are expected due to subsidence in the shaft or at the surface. Horizontal strains will likely be generated over a time frame of several hundred years as maximum subsidence fully develops. Therefore, future structures built at the WIPP should only be subjected to negligible increases in horizontal strain during their lifetime even for the no-backfill case.

The total predicted subsidence in the shaft pillar area is slightly greater than the design criterion established in the Design Validation Final Report (DOE, 1986) (1 inch of subsidence within 500 ft of the waste shaft). However, it is assumed that the design criterion applies only for the operational lifetime of the shaft. Subsidence is expected to be much less during this period and is expected to be below the design criterion.

In summary, no real geomechanical advantage will be gained by placing backfill in any of the WIPP underground areas. Based on the correlation of the subsidence predictions from the various methods, a crushed salt backfill emplaced in the northern experimental area and the shaft pillar area could reduce the total surface subsidence; however, the amount of that subsidence, with or without backfill, would not be significant.

Table ES-1
Summary of Subsidence Prediction Results

Underground Area	Contents of Excavation	Subsidence				
		Mass Conservation (m)	Influence Function Method (m)	NCB Method (m)	FLAC Single-Room Model (m)	FLAC Full-Panel Model (m)
Waste emplacement area[a]	Empty	0.86	0.56	0.73	0.95	0.55
	Waste only	0.62	0.40	0.53	NA	NA
	Waste plus loose backfill	0.55	0.36	0.47	0.33	NA
	Waste plus compacted backfill	0.52	0.34	0.44	0.30	NA
Shaft pillar area	Empty	0.28	0.10	0.04	NA	0.13[b]
	Loose backfill	0.12	0.04	0.02	NA	NA
	Compacted backfill	0.06	0.02	0.01	NA	NA
Northern experimental area	Empty	0.24	0.08	0.02	NA	NA
	Loose backfill	0.11	0.04	0.01	NA	NA
	Compacted backfill	0.05	0.02	0.01	NA	NA

[a]Waste emplacement area includes Panels 1 through 8; 2 through 8 are not yet excavated.
[b]At the Waste Shaft.
NCB = National Coal Board.
FLAC = Fast Lagrangian Analysis of Continua.
NA = Not available.
m = Meters.

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List of Abbreviations/Acronyms

BF1	Half-Panel Room Interaction Model
BF2	Single-Room Maximum Subsidence Model
BF3	Full-Panel Subsidence Model
BLM	U.S. Bureau of Land Management
cal/mol	calorie(s) per mole
CH	contact-handled
cm	centimeter(s)
cm/yr	centimeter(s) per year
deg	degree(s)
DOE	U.S. Department of Energy
DRZ	disturbed rock zone
DVFR	Design Validation Final Report
FEIS	Final Environmental Impact Statement
FLAC	Fast Lagrangian Analysis of Continua
FSAR	Final Safety Analysis Report
FSEIS	Final Supplemental Environmental Impact Statement
ft	foot (feet)
g/cm^3	gram(s) per cubic centimeter
GPa	gigapascal(s)
GPR	ground-penetrating radar
in.	inch(es)
in./yr	inch(es) per year
K	kelvin
kg/m^3	kilogram(s) per cubic meter
lb/ft^3	pound(s) per cubic foot
m	meter(s)
mm	millimeter(s)
mm/yr	millimeter(s) per year
MB139	Marker Bed 139
MPa	megapascal(s)
NCB	National Coal Board
NGS	National Geodetic Survey
NMVP	No-Migration Variance Petition
Pa	pascal(s)
PAD	Performance Assessment Division
RH	remote-handled
SAR	Safety Analysis Report
SNL/NM	Sandia National Laboratories/New Mexico
SPDV	Site and Preliminary Design Validation
TRU	transuranic
WIPP	Waste Isolation Pilot Plant

1.0 Introduction

The Waste Isolation Pilot Plant (WIPP) is a facility designed for the permanent disposal of transuranic (TRU) radioactive waste generated at U.S. Department of Energy (DOE) facilities across the United States. The WIPP is located in southeastern New Mexico 26 miles east of Carlsbad (Figure 1-1). The WIPP underground facilities are excavated 650 meters (m) (2,150 feet [ft]) below the surface in the Salado Formation, a thick bedded salt formation of Permian age (Figure 1-2). The underground facility consists of (1) the main shaft area and associated access drifts; (2) a waste emplacement area to the south of the main shaft area that consists of eight panels, of seven rooms each, to be used for disposal of TRU radioactive waste (only Panel 1 is presently excavated); and (3) an experimental area for nonradioactive experiments developed to the north of the main shaft area. A schematic view of the surface and underground facilities at the WIPP site is shown in Figure 1-3.

The primary purpose of this report was to determine if there is a geomechanical need or advantage to backfilling the WIPP underground. The concept of backfilling the WIPP underground is usually associated with the final sealing of the repository. Since WIPP is designed to be a permanent waste disposal facility, sealing of the repository is a part of the decommissioning process. Decommissioning may include backfilling some or all of the underground workings. This report lists the various proposed operational, long-term performance, and geomechanical uses for backfill in the WIPP underground. The main focus of the report is on the geomechanical uses of backfill; operational and long-term performance uses for backfill are discussed briefly. The main geomechanical effect explored in this report is subsidence, which could affect the stability of facilities at the surface and in the shafts. In addition, subsidence could potentially disturb the Culebra Dolomite or other water-bearing units of the Rustler Formation; however, the effect of any such disturbance on the groundwater flow characteristics in these units is outside the scope of this report and is not investigated here.

Chapter 2.0 of this report summarizes previous discussions of backfill uses published in WIPP project documents. Different areas of the WIPP underground are described as they relate to the use of backfill. Also included are the results of a literature search to locate previous studies containing pertinent information. Backfill and subsidence investigations at the WIPP site and at similar underground excavations, including potash mines located near the WIPP site, are considered.

Chapter 3.0 presents calculational and computer modeling results that help determine the geomechanical effect of backfill on areas within the WIPP underground. Observations and geotechnical data collected at the WIPP site were evaluated to determine if they could be used to estimate expected responses to excavations and interactions of the underground workings. Subsidence prediction methods, including the influence function method and the mass conservation calculation, are used to estimate the amount of subsidence—with and without backfill. Chapter 3.0 also provides a description of the National Coal Board (NCB) empirical method for analysis of subsidence, including the applicability of the NCB method to the WIPP site stratigraphy and mining technique. The NCB method was first applied to a WIPP area potash mine, and the results were then compared to actual measurements. The degree of correlation showed that the NCB method is applicable when used on the WIPP underground workings. The results of the NCB subsidence calculations on the WIPP geometry and stratigraphy are included.

A detailed description of the Fast Lagrangian Analysis of Continua (FLAC) (Itasca, 1991) computer modeling code is also given in Chapter 3.0. FLAC is a finite difference computer code used to calculate displacements around modeled excavations. These displacements indicate the degree of subsidence at the surface. A brief explanation of the computer code and its uses is offered. Three FLAC models are discussed along with their assumptions and results.

Chapter 4.0 presents conclusions based upon the report findings. Chapter 5.0 provides the references used in the report. Appendix A presents brief descriptions of operational and performance based uses of backfill at the WIPP. These uses will not be addressed in detail in this report.

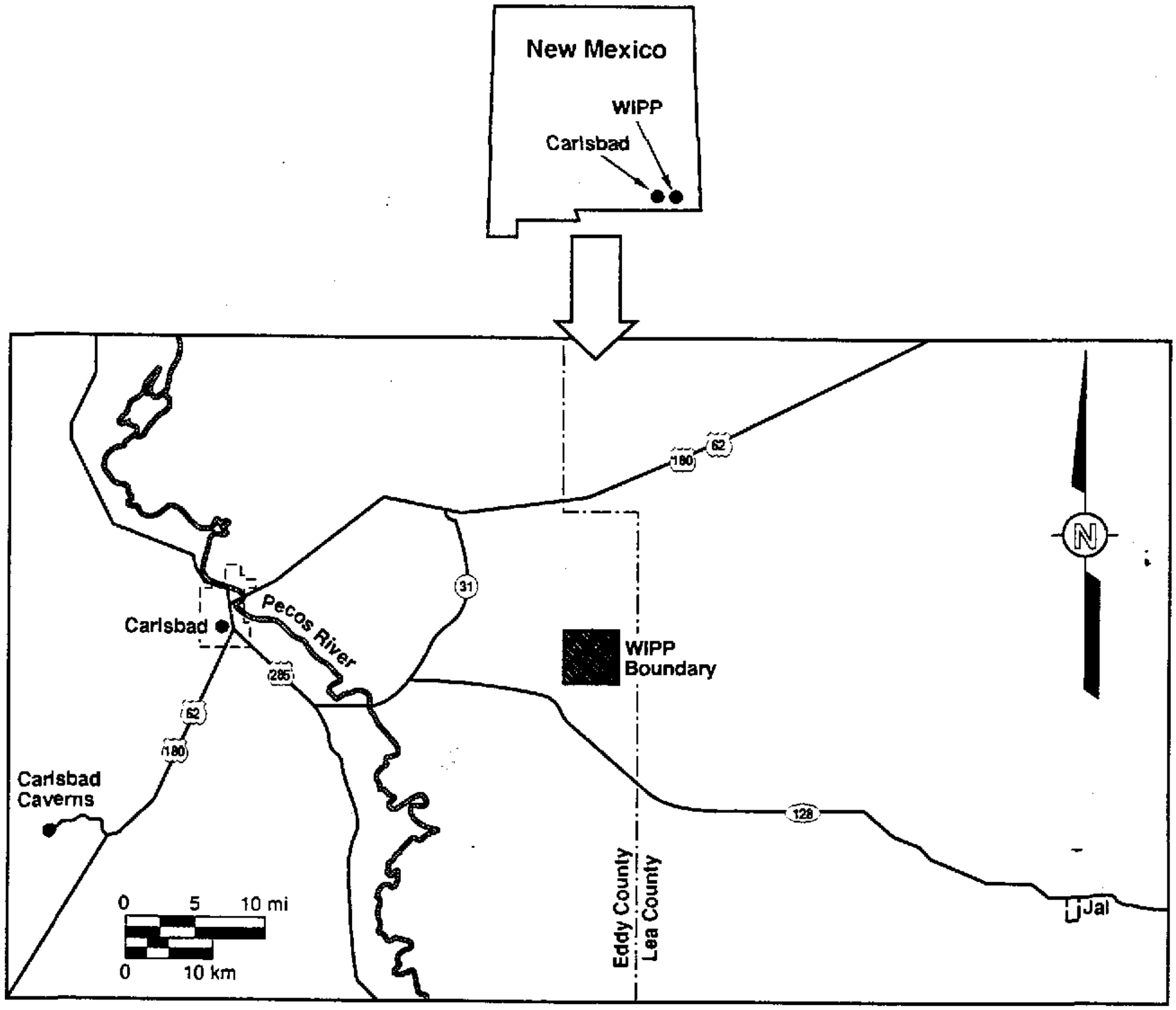

Figure 1-1
WIPP Location in Southeastern New Mexico

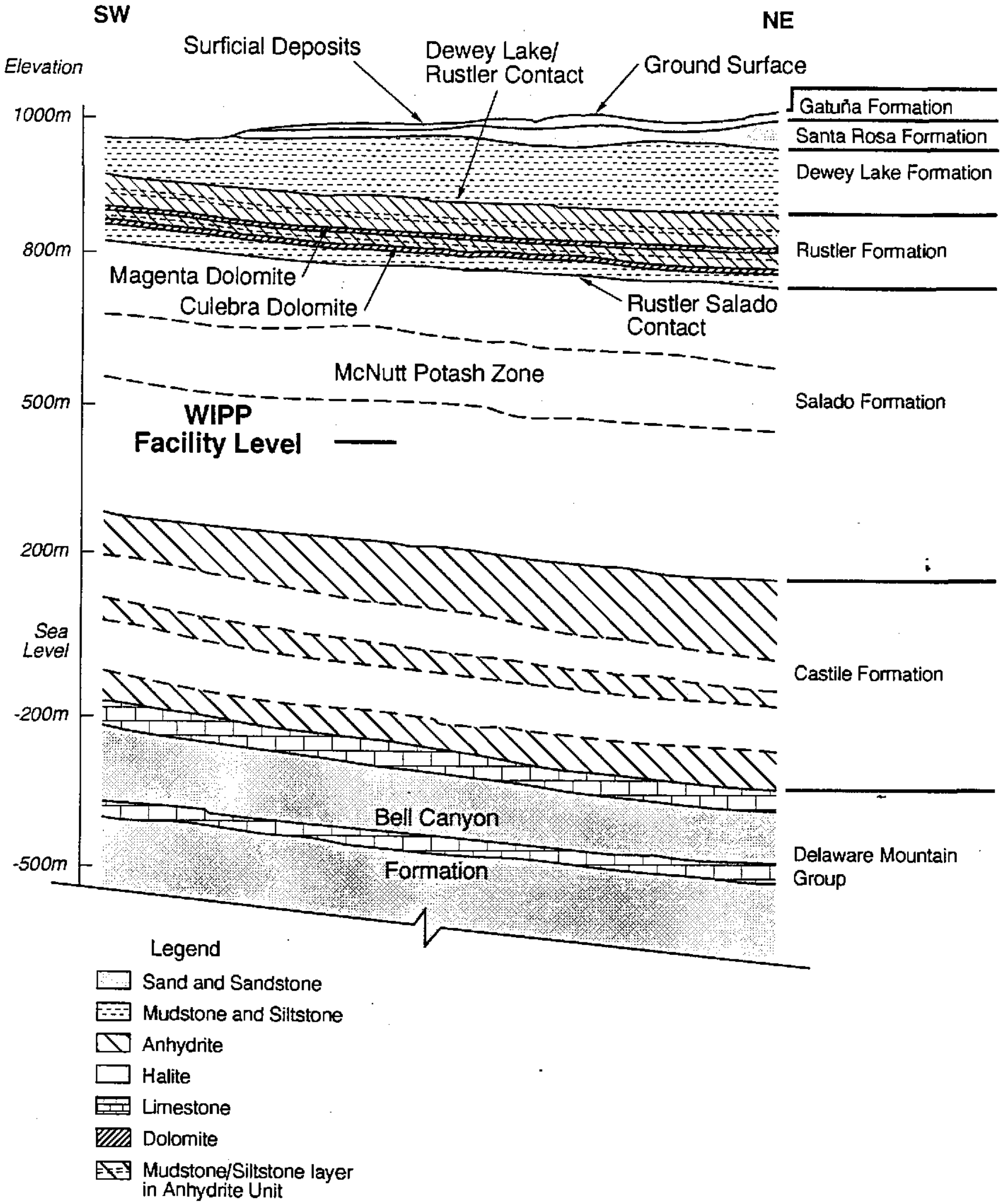

Figure 1-2
Generalized Stratigraphic Cross Section of the WIPP Site

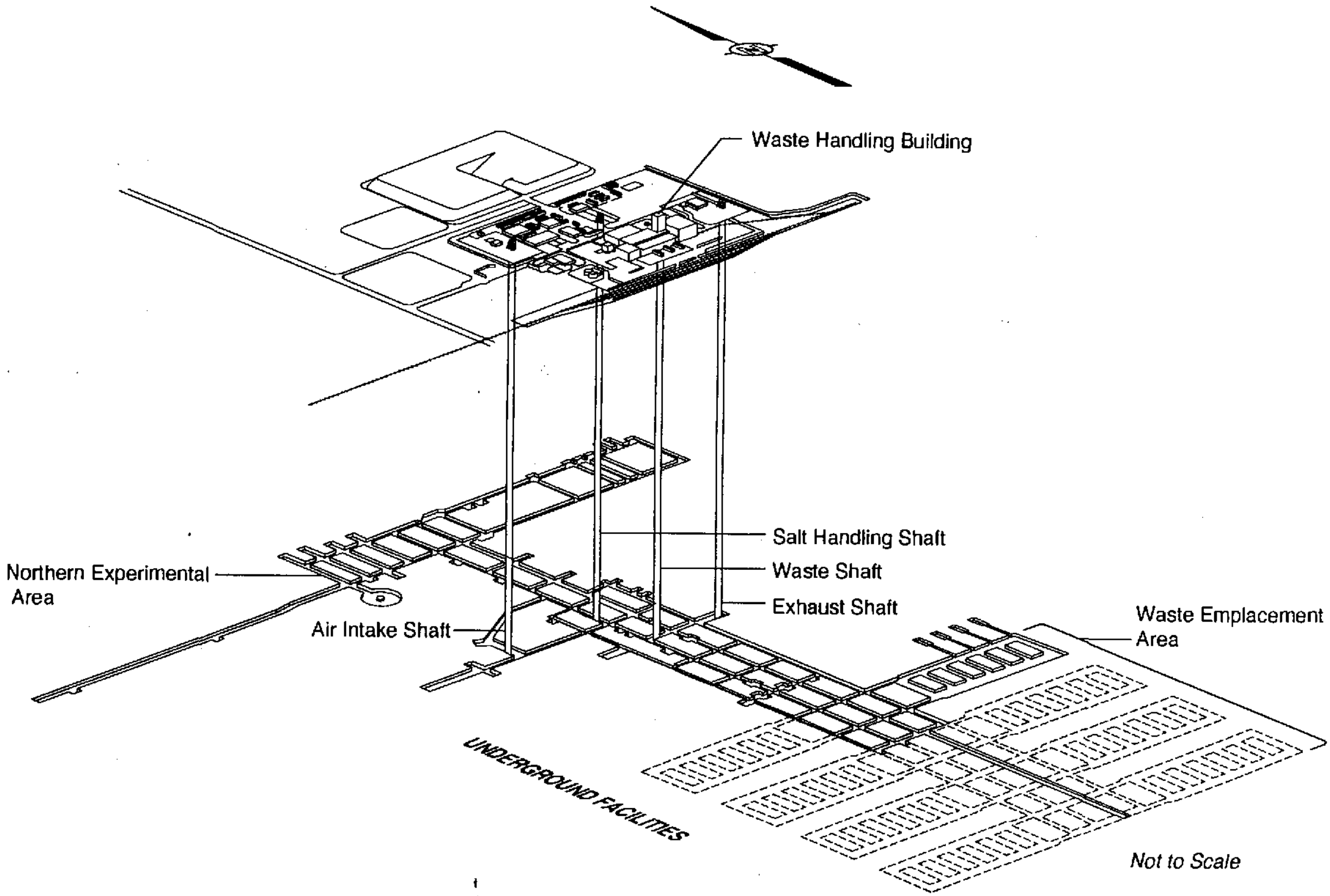

Figure 1-3
Surface and Underground Layout of the WIPP Facility

2.0 Background of Backfill and Subsidence Investigations at the WIPP Site and Other Underground Operations

This chapter summarizes previous discussions of backfill and backfill uses that have been published in WIPP project documents. It also discusses previous backfill and subsidence investigations at the WIPP and backfill and subsidence investigations at other underground operations that have similar or analogous stratigraphy and geology.

2.1 Backfill Uses

This section summarizes previous discussions of backfill found in WIPP project documents, proposed uses for backfill at the WIPP site, and descriptions of the areas of the WIPP underground where backfill may be placed.

2.1.1 Backfill Discussions in Project Documents

The purpose of this section is to provide an overview of previous discussions of backfill found in WIPP project documents, including the Safety Analysis Report (SAR), the Final Safety Analysis Report (FSAR), the Final Environmental Impact Statement (FEIS), the Final Supplemental Environmental Impact Statement (FSEIS), the No Migration Variance Petition (NMVP), and the Design Validation Final Report (DVFR).

2.1.1.1 Safety Analysis Report and Final Safety Analysis Report

The SAR and the FSAR discuss the use of backfill as part of the decommissioning process at the WIPP. The following are excerpts from those documents:

> About 15 percent of the salt excavated from the storage rooms will be retained underground for backfilling. . . . Backfilling of storage rooms is operationally concurrent with waste storage operations. At decommissioning, backfill operations include removing the salt from the surface storage pile, crushing and drying it, and transferring it to the underground storage areas to be used as backfill (Section 3.2.5.2 of the SAR [DOE, 1980a]).

> If TRU waste containers are not retrieved, any contact-handled (CH) and remote-handled (RH) waste emplacement entries not previously backfilled will be filled with crushed and dried salt taken from the surface storage pile. If the waste is retrieved, the areas will be backfilled as required. After the shaft equipment is removed, the shafts will be filled with salt taken from the surface storage pile up to the approximate height of the

Salado Formation. The remaining backfilling operation will be completed using other appropriate materials. The final sealing of the shafts will be accomplished by acceptable borehole plugging techniques. These plugs will be subject to quality controls to ensure that they conform to the performance specifications (Section 3.5.2 of the SAR [DOE, 1980a]).

Decommissioning features included in the design of all the WIPP structures and equipment are requirements for . . . backfilling and sealing the underground areas and shafts (Section 3.4 of the FSAR [DOE, 1990a]).

The FSAR also discusses the potential for surface subsidence in the area surrounding the shafts:

The total amount of surface subsidence is dependent on the amount of salt creep that will occur due to the unfilled volume left within the underground opening, the ultimate extraction ratio, and the properties of the rock overlying the waste storage level. Subsidence calculations take into consideration all of these factors. The amount of subsidence that is used for the design of surface structures is based on the amount of creep calculated to occur during the life of the facility and during the compaction of the structural backfill to some final extraction ratio. Preliminary calculations show maximum surface subsidence to be 12 to 15 inches over a period of 35 years, based on the validated room configuration. . . . The reference design subsidence criterion is considered validated on a computational basis rather than actual measurement data. A review of this conclusion may be required later, when a history of actual subsidence is available (Section 2.10.1.1 of the FSAR [DOE, 1990a]).

It should be noted that these statements from the SAR and FSAR are general and do not provide any backfill specifications or design criteria.

2.1.1.2 Final Environmental Impact Statement and Final Supplemental Environmental Impact Statement

In the FEIS (DOE, 1980b) backfill is considered for use in the CH TRU waste emplacement rooms to reduce potential fire hazards. It was also suggested for use in decommissioning alternatives that involve entombment of the waste in the waste emplacement rooms (Section 8.11 of the FEIS [DOE, 1980b]). The potential to reduce surface subsidence is also described. In the FEIS, it is estimated that a 4.9-m (16-ft) high cavity would cause surface subsidence of 30 centimeters (cm) (1 ft) at 70 percent backfill (crushed salt backfill placed at a density of 70 percent of intact salt) and 49 cm (1.6 ft) at 50 percent backfill of crushed salt. Due to the plasticity of salt, closure would occur rapidly and be transferred to the overlying Rustler Formation (Section 9.7.2.2 of the FEIS [DOE, 1980b]).

In the FSEIS (DOE, 1990b), a potential breach of the water-bearing Culebra Dolomite and the subsequent possibility of transmitting radionuclides to the accessible environment are stated as a cause for concern (Section 6.3.2 of the FSEIS [DOE, 1990b]). The FSEIS indicates that the detailed extent of disruption to the overlying units caused by this breach was unknown at that time and would be difficult to accurately predict.

A justification for backfilling is provided in the FSEIS:

> The reason for backfilling the WIPP disposal rooms and access tunnels (i.e. filling in spaces that remain open after waste has been emplaced) would be to shorten the estimated "time for closure" of the disposal room. (The time for closure is the time required for salt creep to reduce room void space and to compact the waste to a final state.) The rapid entombment may minimize brine inflow and thereby decrease the amount of gas generated by the corrosion of waste drums and the iron-bearing constituents of the waste. Sorption of brine and removal of generated gasses are other potential uses for backfill. In these applications, additives would be mixed with the crushed salt used for backfill (Section 6.3.2.1 of the FSEIS [DOE, 1990b]).

Section 6.3.2.2 of the FSEIS (DOE, 1990b) explains that, since 1980, studies have been concerned with brine inflow and generation of gas from the corrosion of waste drums. Originally, crushed salt was the only candidate for backfill; however, concerns related to potential brine inflow and gas generation have necessitated consideration of additives and alternate materials. A 70 percent/30 percent (by weight) crushed salt/bentonite mixture is being considered as a potential backfill candidate (Butcher, 1991) to absorb brine and radionuclides. Gas-getters are also under consideration to reduce the build-up of gas generated by the waste canisters (Brush, 1990). Calcium carbonate and calcium oxide are being considered to reduce the partial pressure of carbon dioxide, and copper sulfate is being considered to allow corrosion of the drums without the production of hydrogen. The effectiveness of these gas getters has yet to be determined.

The discussions on backfill provided in the FEIS and the FSEIS are general and do not provide any backfill specifications or design criteria.

2.1.1.3 No-Migration Variance Petition

In the NMVP (DOE, 1990c), the use of backfill is discussed as part of closure and postclosure (decommissioning) care. Section 2.6.9 of the NMVP provides a brief description of the activities that are involved in the decommissioning of the WIPP site as follows:

> Briefly, decommissioning will involve decontaminating (if necessary) and dismantling the surface facilities and backfilling the waste rooms, tunnels, and shafts. Any contaminated surface equipment and debris will be placed in the rooms or drifts prior to backfilling. Salt originally excavated from the WIPP facility will be used for backfilling. The salt will be compacted as closely as possible to its original density (Section 2.6.9 of the NMVP [DOE, 1990c]).

More detail on the use of backfill is provided in Appendix C of the NMVP, titled "Closure and Post Closure Plans," which proposes pneumatic backfilling techniques (DOE, 1990c). Again, no specifications are provided, but it states that salt will be used as backfill and implies that it will be emplaced and compacted to a relatively high density (approximately 70 to 75 percent of intact salt density). This can be considered typical of good, conventional backfilling practice.

2.1.1.4 Design Validation Final Report

Backfilling of waste emplacement rooms was initially proposed to help stop fire propagation based on an accident scenario in which spontaneous ignition of the contents of a CH-TRU waste container results in fire propagation to adjacent containers (DOE, 1980a). However, a final report to the DOE from the Waste Drum Fire Propagation Task Force (Westinghouse, 1986a) concluded that the fire propagation scenario was not credible. Consequently, salt backfill will not be required in the storage area drifts and rooms for this specific purpose.

A design criterion within the DVFR was established for surface subsidence in the area of the waste shaft. The design criterion is stated as follows:

> The design criteria require that subsidence due to underground excavation not exceed one inch within a 500-foot (ft) radius of the waste shaft. The layout of the underground facilities and the extraction ratio requirements

were established to comply with this criteria (Section 6.5 of the DVFR [DOE, 1986]).

This is the only design criterion specifying a maximum allowable subsidence. It is unclear whether the 1-inch (in.) criterion refers to total subsidence or to differential subsidence (tilting) within the 500-ft-radius area around the shafts. The DVFR indicates that the 15 percent extraction ratio design requirement for the 1,100-ft-radius shaft pillar (DOE, 1986) will allow this subsidence design criterion to be met, though it is uncertain whether or not the conclusion reached in the DVFR is based on the shaft pillar drifts being backfilled. It is assumed that the design criterion applies to acceptable subsidence in the vicinity of the Waste Shaft during the operating life of the WIPP underground (i.e., during the period of time the Waste Shaft is in use and when subsidence would have an effect on the operations in the shaft).

A subsidence monitoring network is gradually being installed to determine surface subsidence during the operating life of the facility. Data from this network are limited, and at present the network only extends over part of the northern experimental area and part of the shaft pillar area.

2.1.2 Backfill Uses

This section discusses the various proposed uses for engineered backfill. Engineered backfill may be crushed salt or may contain a combination of crushed salt and additives that enhance the physical and chemical properties of the backfill material. The backfill uses presented here include operational, long-term performance, and geomechanical uses.

Operational uses for backfill include:

- Backfill around waste containers for fire suppression
- Backfill above the waste containers to function as a cushion in case of a roof fall.

The impact of backfill around waste containers on the retrievability of those containers is another operational aspect of backfill.

The uses of backfill that have been proposed to enhance long-term performance include:

- Backfill in the access drifts as an engineered barrier or sealing material
- Backfill additive as a gas-getter to react chemically with gases that may be generated by the waste
- Backfill additives to promote adsorption of radionuclides within the waste emplacement rooms
- Backfill additives to absorb brine that may flow into the waste emplacement rooms
- Backfill to reduce the disturbed rock zone (DRZ) around drift seal locations
- Backfill additives as intrusion markers.

The proposed geomechanical uses for backfill include:

- Backfill to reduce instability in adjacent openings
- Backfill to reduce subsidence in the overlying strata (specifically the Culebra) and at the surface.

When available, information on the validity of each backfill use is also presented. In-depth investigations of operational and long-term performance uses of backfill are beyond the scope of this report, however, brief discussions on the proposed uses for backfill that relate to operational or performance issues are presented in Appendix A to inform the reader of the other potential uses for backfill materials in the WIPP underground. Geomechanical uses are described in detail below and are investigated in Chapter 3.0.

2.1.2.1 Backfill to Reduce Instability in Adjacent Openings

Backfill could be placed in abandoned or unused drifts or rooms that are located adjacent to working drifts to reduce instabilities in the working drifts. Once placed, the backfill would reconsolidate as the excavation walls, roof, and floor began to creep in. Stress would then build within the backfilled excavation, slowing the creep and allowing for stress redistribution. The stability of nearby open excavations would be enhanced by this stress redistribution.

This use of backfill might be applicable in areas where two or more drifts are parallel with relatively close proximity or where two drifts intersect. Chapter 3.0 of this report provides a more detailed discussion of this type of use, along with the results of numerical modeling of parallel drifts and the results of underground observations of stability of isolated drifts, parallel drifts, and intersecting drifts.

2.1.2.2 Backfill to Reduce Subsidence

Surface subsidence at the WIPP site is expected to eventually occur as the rock mass deformation caused by the excavation propagates upwards. Potential subsidence, as evidenced at the surface, is important in the short-term due to its effect on the structural stability of the buildings at the surface. The long-term effects of subsidence are of a greater concern to the long-term performance of the disposal system, since it may disrupt the formations between the excavation and the surface. The Culebra Dolomite is located above the repository horizon and has been identified as a potential flow path for radionuclide release (Lappin et al., 1989). Depending on the amount, subsidence may induce or enhance fracturing in the Culebra Dolomite, which in turn could increase its ability to transmit water by enhancing the permeability. Also, the effects of subsidence create some uncertainty to the modeling of flow and transport within the Culebra Dolomite. For this report, considerable analysis was performed to predict the degree of subsidence at the surface and at the Culebra Dolomite unit over the various areas of the WIPP underground. The analyses also look at the effect, if any, that backfill emplacement will have on the reduction of subsidence. The analyses performed include empirical estimating techniques and mathematical modeling techniques.

2.1.3 Backfill Areas

The underground workings at the WIPP site can be broken into three major areas based upon operations, relative location, and backfill needs. These three areas are shown in Figure 2-1 and consist of:

- The waste emplacement area (Panels 1 through 8 to the south)
- The northern experimental area
- The access drifts located within the "shaft pillar" area.

2.1.3.1 Waste Emplacement Area

The waste emplacement area consists of the eight waste emplacement panels and four main access drifts (two drifts for fresh air and two drifts for return air) located at the southern end of the underground repository (only Panel 1 is excavated at present). Each waste emplacement panel consists of seven waste emplacement rooms measuring 4 m high, 10 m wide, and 91.5 m long (13 by 33 by 300 ft). The rooms are separated from each other by 30.5-m-wide, 91.5-m-long (100-ft-wide, 300-ft-long) pillars. Panel entries at each end of the waste emplacement rooms are also 10 m (33 ft) wide and 4 m (13 ft) high. The waste emplacement rooms and the panel entries will be used to store waste. Each panel is separated from the main access drifts by a 61-m-wide, 91.5-m-long (200-ft-wide, 300-ft-long) barrier pillar. The 61 m (200 ft) of panel entry drift adjacent to the barrier pillar is the proposed location for the panel entry seals (DOE, 1990a).

The main access drifts into the waste emplacement area, which extend from the north end of the waste emplacement area to the south end of the underground workings (Figure 2-1), may also be used for waste emplacement. An option exists to use these access drifts as alternate storage panels. If this option is executed and waste is to be placed in the main access drifts, then the drifts will be similar to waste emplacement panels, and the uses and constraints of backfilling these drifts will be similar to the uses and constraints mentioned above for the waste emplacement area.

2.1.3.2 Northern Experimental Area

The northern experimental area is located in the northern section of the underground facility (Figure 2-1). This area includes the experimental rooms, the Site and Preliminary Design Validation (SPDV) rooms, and their associated access drifts. No waste has been, or will be, emplaced in this area.

Most of the experiments performed in the northern experimental area are complete. Some parts of this area have been closed or have limited access because of excavation instabilities.

2.1.3.3 Shaft Pillar Area

For the purposes of this report, the shaft pillar area consists of all drifts and excavated rooms located between the waste emplacement area and the northern experimental area (Figure 2-1).

The main access drifts within the shaft pillar will need to remain open during the operating life of the underground facility; therefore, backfill cannot be emplaced in most of this area until decommissioning. Backfill material could be placed immediately in some of the crosscuts in the shaft pillar area that are not needed for access or ventilation, if it is determined that backfill should be used to improve stability in adjacent drifts. This is investigated in Section 3.5 of this report.

2.2 Previously Published Investigations of Backfill Materials and the Use of Backfill at the WIPP Site

Many previous investigations have been performed on backfill materials and the use of backfill at the WIPP site. Most of these investigations have focused on the chemical and physical properties of different backfill materials and additives. This section briefly discusses some of these investigations, focusing on the geomechanical properties of the backfill materials and on how backfilling relates to the geomechanical issues described in Section 2.1.2.

As presented in Section 2.1.1, several project documents discuss backfilling parts of the WIPP underground (DOE, 1980a; DOE, 1990a; DOE, 1980b; DOE, 1990b; DOE, 1986). The focus of backfilling, in previous investigations has been emplacement around the waste. Backfill has also been discussed in these project documents as an engineered barrier—to be placed in the access drifts between the shafts and the waste emplacement rooms as a long-term seal material. Lappin et al. (1989) discuss the use of various materials as backfill or backfill additives. Bentonite would be added for absorption of free brine and adsorption of radionuclides. Crushed salt backfill would be used in access drifts between the shafts and the waste emplacement area, and a salt/bentonite mixture would be used within the waste emplacement rooms (Lappin et al., 1989). Butcher (1991) also investigated a salt/bentonite mixture for use around the waste, focusing on the brine absorption and radionuclide adsorption qualities of the bentonite additive.

A considerable amount of investigation has been performed on backfill in the WIPP underground as an engineered barrier (Nowak, 1980a; Nowak, 1980b; Nowak, 1981a; Nowak, 1981b; Nowak, 1982; Tyler et al., 1988; Lappin et al., 1989). These investigations considered pure crushed salt backfill or mixtures of crushed salt and additives, such as bentonite.

The consolidation of crushed salt backfill and the relationship between porosity and permeability of the crushed salt as it reconsolidates has been investigated by Holcomb and Hannum (1982), Pfiefle and Senseny (1985), Yost (1986), Yost and Aronson (1987), Case et al. (1987), Holcomb and Shields (1987), Sjaardema and Krieg (1987), Zeuch and Holcomb (1991), and Valdivia (1994). Some of these investigations indicate that crushed salt offers little resistance to creep closure until it has reconsolidated to 94 percent of the density of intact WIPP salt (Sjaardema and Krieg, 1987). At the relative density of 94 percent of intact salt, laboratory tests have shown that the intrinsic permeability of reconsolidated crushed salt is approximately 1×10^{-20} square meters (10 nanodarcy), which is approximately equivalent to the permeability of intact salt at the WIPP (Holcomb and Shields, 1987). Once reconsolidated, the crushed salt backfill would likely become an effective engineered barrier to brine and radionuclide migration.

As described in Section 2.1.2, there are two major geomechanical uses for backfill in the WIPP underground—to reduce instability in adjacent openings and to reduce subsidence at the surface and in overlying water-bearing strata. This section discusses the previous investigations, or lack of previous investigations, of these uses.

Using backfill to reduce the instability in adjacent openings has not been investigated in detail. Stormont et al. (1991) investigated changes in permeability of intact rock salt due to nearby excavations, but the investigation was primarily focusing on determining the propagation and extent of the DRZ as an excavation was advanced.

Subsidence predictions for the WIPP site have been presented in previously published reports. The FEIS (DOE, 1980b) discusses the effects of subsidence and provides a calculated prediction of the lateral extent of surface subsidence and the predicted maximum subsidence. The area expected to be affected by surface subsidence was estimated in the FEIS at approximately 4 square kilometers (1,000 acres) and extended 640 m (2,100 ft) around the outside edge of the underground workings. This estimate was based on the following assumptions:

- The "angle of draw" or the "limit angle" (the angle between the vertical and a line connecting the edge of the surface subsidence and the edge of the underground opening) is assumed to be 45 degrees. This assumption was based on a Bureau of Land Management (BLM) report on the area potash mines and the typical angle of draw at those mines (BLM, 1975).

- The depth of the WIPP underground workings was assumed to be 640 m (2,100 ft).

- The area of the WIPP underground workings was assumed to be 0.72 square kilometers (180 acres).

The FEIS (DOE, 1980b) used the following equation and assumptions in performing the calculation of the estimated maximum subsidence:

$$S_{max} = f\ M\ b\ a$$

Where,

S_{max} = Maximum subsidence
f = Subsidence factor (the ratio of vertical surface displacement to cavity height)
M = Height of the underground excavation (cavity height)
b = Percent of excavation remaining after backfill
a = Extraction ratio.

The equation assumes the following:

- The mine is at the critical extraction width (the width of the area that must be extracted to produce maximum subsidence at the center of a subsidence trough)

- The subsidence factor (f) was assumed to be 0.67, based on the ratio at nearby potash mines (BLM, 1975)

- The extraction ratio (a) was assumed to be 30 percent, based on the preliminary designs of the WIPP underground

- The cavity height (M) was assumed to be 4.9 m (16 ft).

The results of the calculations presented in the FEIS indicate that surface subsidence of approximately 30.5 cm (1 ft) could be expected at 70 percent backfill (crushed salt backfill placed at a density of 70 percent of intact salt) and approximately 49 cm (1.6 ft) at 50 percent backfill. The predicted surface subsidence with no backfill was not presented in the FEIS calculations. However, using the equation and assumptions provided in the FEIS, the estimated surface subsidence without backfill would be approximately 1 m (3.2 ft). The predicted surface subsidence ". . . of 1 to 1.6 ft will be insignificant inasmuch as the natural relief at the site is greater; furthermore, there is no integrated surface drainage to disturb" (DOE, 1980b).

In April 1986, the Technology Development Group at the WIPP site transmitted a letter to the WIPP Deputy Project Manager (Westinghouse, 1986b) discussing various subjects associated with the use of backfill in the WIPP underground. Among the subjects addressed were the use of backfill to suppress the propagation of waste fires (discussed in this report in

Section 2.1.2 and Appendix A) and to reduce subsidence. The Technology Development Group concluded that "(s)urface subsidence will likely not be a major concern with or without backfill." The group also indicated that expected surface subsidence could range from less than 15 cm (0.5 ft) (based upon calculations performed by the Technology Development Group) up to 49 cm (1.6 ft) (based on the calculations presented in the FEIS [DOE, 1980b]). An excerpt from the Technology Development Group's letter is presented below.

> The subsidence issue as related to the backfill question, however, is more closely related to disposal system performance than purely a question of surface subsidence. Surface subsidence of 0.5 to 1.6 feet may not have significant effects on the strata overlying the Salado, however, the degree of subsidence, without backfill, which could affect disposal system performance either in the Salado or in the overlying strata has not been determined or evaluated.

The FSAR (DOE 1990a), in Section 2.10.1.1, discusses the expected maximum surface subsidence in the shaft pillar area and the waste emplacement area. The amount of surface subsidence used for the design of surface structures is based on the amount of creep expected to occur before the complete consolidation of any backfill. Based on these assumptions, the FSAR presents an expected maximum surface subsidence of 30.5 to 38 cm (12 to 15 inches) over a period of 35 years (DOE, 1990a). (The amount or type of backfill assumed for this estimate is not indicated in the FSAR). The range of predicted surface subsidence is similar to that presented in the FEIS (DOE, 1980b).

The WIPP Performance Assessment Division (PAD) of Sandia National Laboratories/New Mexico (SNL/NM) has also performed an evaluation of subsidence at the WIPP (SNL/NM, 1991). The calculations performed by the WIPP PAD were based on the conservation of volume. It was assumed that the volume of the underground excavations would be filled by waste, backfill, and the movement of the overlying strata. The amount of pore space within the waste emplacement rooms would be reduced as the intact salt began to creep in and as the backfill and waste were consolidated. This reduction in void volume within the waste emplacement rooms would be completely transmitted to the surface in the form of subsidence. The areal extent of the surface subsidence is dependent on the angle of draw above the underground excavation. This method of subsidence prediction assumes that the total volume of the surface subsidence (the areal extent multiplied by the vertical subsidence) is equal to the reduction in the void volume within the waste emplacement area. The method also assumes that the vertical subsidence is equally distributed over the entire area of the subsidence. Therefore, the larger the angle of draw is, the larger the areal extent of the surface subsidence and the smaller the vertical subsidence. The results of the WIPP PAD calculations indicate that the average surface subsidence over the waste emplacement area is expected to be between 9 and 13 cm (0.29 and 0.43 ft), using an angle of draw ranging from 35 to 25 degrees, respectively. The calculation is also based upon the following set of assumptions (SNL/NM, 1991):

- The extraction ratio for the waste emplacement area of the WIPP underground is 0.22
- The excavated room height is 4 m (13 ft) at a depth of approximately 640 m (2,100 ft)
- The waste emplacement area is modeled as a cylindrical excavation with a radius of 394 m (1,293 ft)
- The waste emplacement rooms are filled with a mixture of waste and a backfill made up of 70 percent crushed salt and 30 percent bentonite
- The initial porosity of the waste/backfill mixture is 63 percent
- The final consolidated porosity of the waste/backfill mixture is 16 percent.

The WIPP PAD (SNL/NM, 1991) also assessed the effect of the predicted subsidence on the area hydrology. They found no direct information or data available on the effects of subsidence on the overlying groundwater flow system in the area.

2.3 Previous Backfill and Subsidence Investigations at Non-WIPP Locations

Investigations of backfill emplacement and consolidation and investigations of subsidence have been performed for mining operations other than the WIPP. Most of these investigations have been associated with potash mining around the world. Investigations have also been performed on the consolidation of crushed salt backfill at a proposed nuclear waste repository in Germany. This section of the report presents a summary of these investigations and a summary of subsidence investigations at potash mining operations that may be considered similar (i.e. similar depth and/or stratigraphy) to the WIPP site.

2.3.1 Backfill Investigations

Most investigations of crushed salt as a backfill material have been associated with the WIPP site; however, a limited number of investigations on crushed salt backfill characteristics at locations other than the WIPP site have been performed. Korthaus (1984) discusses the consolidation of crushed salt as a backfill material for a proposed underground repository in bedded salt located in Germany. The proposed repository is for the storage of intermediate-level nuclear waste. Korthaus presents a material model for crushed salt consolidation and the effect of the consolidation on the closure of excavations in salt. Korthaus' model is largely based on models developed for the WIPP site by Holcomb and Hannum (1982) and has been modified slightly to better fit the specific conditions and crushed salt characteristics associated with the German repository.

Another investigation discusses the use of crushed salt backfill in potash and salt mines to reduce surface subsidence and to remove surface tailing piles (Van Sambeek, 1992). This investigation utilizes previous crushed salt backfill investigations that were performed for the WIPP, including laboratory testing results, material constitutive laws, modeling results, and field measurements. The investigation assumes that, while some of the information is site-specific, most of the data and modeling procedures used are applicable to other sites and mining operations. The consolidation model developed for the WIPP (Sjaardema and Krieg, 1987) was used to model the creep consolidation of salt tailings under Canadian potash mine operations in Saskatchewan. The mathematical model and typical parameters for crushed salt were presented. The WIPP consolidation model was fitted to laboratory data from consolidation tests performed on potash tailings.

De Souza (1992) also discusses the use of crushed salt backfill in salt and potash mines to maintain local and regional ground stability during production, to limit creep deformation, and to control ground subsidence. De Souza investigated the effect of initial moisture content on the emplacement density and final consolidated density of crushed salt backfill material. The optimum moisture content to achieve the maximum emplacement and final consolidation densities was determined to be between 8 and 10 percent. The emplacement density for the crushed salt backfill ranged from 1.31 to 1.71 grams per cubic centimeter (g/cm^3) (82 to 107 pounds per cubic foot [lb/ft^3]), with corresponding initial porosities of 41 to 21 percent, respectively. The results of the investigation by De Souza indicated that the emplacement of a compacted crushed salt backfill material would be capable of reducing the potential subsidence due to full extraction mining by approximately 64 percent.

2.3.2 Subsidence Investigations

Subsidence investigations have been performed at many mine locations around the world, including mining sites associated with bedded potash and halite deposits in Saskatchewan, Spain, France, and southeastern New Mexico. The Saskatchewan potash mines are similar to the WIPP in some respects. They are approximately 1,000 m (3,300 ft) deep and have a slightly higher extraction ratio of 35 to 50 percent (Steed et al., 1985). Potash mines located in Spain also have similarities to the WIPP. These mine depths range from 200 to 460 m (650 to 1,500 ft), with weak overlying layers of sandstone, siltstone, and clay (Whittaker and Reddish, 1989). The extraction method used is long-wall mining, and therefore, the extraction ratio is much higher than that for WIPP. The potash mining operation at Alsace, France, also uses a long-wall extraction method, with an extraction ratio of approximately 50 percent at a depth of approximately 460 to 520 m (1,500 to 1,700 ft).

The stratigraphy for the potash mines located in southeastern New Mexico in the vicinity of the WIPP site is very similar to the stratigraphy over the WIPP site. The potash mines are located stratigraphically above the location of the WIPP site in the McNutt potash zone. The depth of these New Mexico potash mines ranges from approximately 275 to 610 m (900 to 2,000 ft), with extraction ratios ranging from 65 to 97 percent (Powers, 1993). The subsidence investigations associated with each of these similar sites is presented below.

2.3.2.1 Saskatchewan, Canada

The Saskatchewan potash mines are located at a depth of approximately 1,000 m (3,300 ft) and have an extraction ratio of 35 to 50 percent. Steed et al. (1985) and Bawden and Mottahed (1986) describe the use of an empirical subsidence prediction method that is applied to these potash mines. Existing subsidence prediction methods were reviewed, and subsidence data from five producing potash mines in the Saskatchewan potash region were used to determine the applicability of the methods (Steed et al., 1985). The comparison of the subsidence data with the prediction methods indicated that a zone-area influence function method (described in more detail in Section 3.3) provided the best correlation to field measurements. The data also indicated that subsidence over these potash mines tends to be time-dependent. The plastic nature and low strength of the evaporites appear to cause subsidence to occur in two stages: an initial high rate of subsidence occurring soon after excavation (100 to 200 days), followed by a lower, more constant subsidence rate. Steed et al. (1985) also indicated that the empirical subsidence prediction method developed by the NCB (1975) for use with European long-wall coal mining operations was not applicable to the Saskatchewan potash mines, because of differences in mining method, material properties, and the absence of time-dependency in the prediction method.

2.3.2.2 Spain

Investigations of subsidence and subsidence prediction at the Esparza Mine in Spain were summarized by Whittaker and Reddish (1989). Long-wall mining techniques are used in the 350- to 460-m (1,150- to 1,500-ft) deep mine to remove two 1.8- to 2.4 m- (6- to 8-ft) thick potash beds. Observations of surface subsidence at this mine were qualitative rather than quantitative and indicated that the surface and subsurface beds exhibited delayed subsidence behavior due to the plastic nature of the overlying strata.

Salas (1979) evaluated subsidence at a second potash mine in Spain. This mine was also a long-wall mining operation extracting a 1.8-m (6-ft) seam at a depth of 200 m (650 ft). Salas compared the development of subsidence in relation to face advance with the predicted subsidence development based on the NCB method. There was close agreement exhibited between the potash mining results and the NCB-predicted relationship. The major difference between the NCB prediction and the observed subsidence was the rate at which the subsidence occurred. The subsidence over the potash mine occurred very slowly during the early stages relative to the predicted development but then developed rapidly along the lines of a classic subsidence trough profile (Whittaker and Reddish, 1989). The observations by Salas (1979) and Forster (1967) indicated that the angle of draw from the vertical for this potash mine was fairly steep, ranging from 25 to 28 degrees, and that the maximum surface subsidence was 60 to 67 percent of the extracted seam thickness. (The extraction ratio for the area was not reported.)

2.3.2.3 Alsace, France

Observations of subsidence at a potash mine in Alsace, France, are discussed by Whittaker and Reddish (1989). Extraction of a 2.1-m (7-ft) bed at a depth of 460 to 520 m (1,500 to 1,700 ft) was performed with long-walls of 50 to 80 m (165 to 260 ft) in width and support pillars approximately 70 m (230 ft) wide. The resulting maximum subsidence observed was 1.6 m (5.25 ft), or approximately 75 percent of the extracted seam thickness over a two-year period. (As before, the extraction ratio for the area was not reported.) The intervening support pillars did not result in any significant, observable hump effects developing in the surface subsidence profile. The subsidence developed slowly initially, then the main trough developed fairly rapidly after approximately 50 percent of the maximum subsidence had been attained. Details on Alsace potash strength properties, pillar behavior, and general subsidence have been discussed by McClain (1963) and Potts (1964).

2.3.2.4 Southeastern New Mexico

The majority of the investigations of subsidence associated with potash mines in southeastern New Mexico were performed by potash mining companies in the area and their consultants. The reports of these investigations are often proprietary information and are rarely published. A summary of some of these reports and information received directly from the area potash mines is presented by Powers (1993) which has limited distribution. Subsidence observations from these WIPP area mines are extremely valuable for estimating the ground reaction and the amount and extent of surface subsidence to be expected over the WIPP underground. However, there are limitations to applying the potash mine subsidence data to the WIPP site. Although the WIPP site is comparable to the potash mines in southeastern New Mexico, there are differences in stratigraphic position, depth, extraction ratio, and layout. However, the overlying stratigraphic units and water-bearing units are similar, as is the surface topography. The depth of the WIPP repository (approximately 650 m [2,150 ft]) is greater than the depth of most of the area potash mines. Only one mine, referred to as Potash Mine #5, is of similar depth.[2] Potash Mine #5 operates at depths of about 600 m (2,000 ft) and extracts ore from high in the McNutt potash zone. The WIPP is located stratigraphically much lower than even the lowest potash mines in ore zone 1, near the base of the McNutt potash zone. At the WIPP site, the base of the McNutt potash zone is about 150 m (490 ft) above the repository horizon. The lower extraction ratios within the potash mines are about 65 percent, while local extraction ratios approach 97 percent at one mine. The proposed WIPP extraction ratio is about 22 percent (SNL/NM, 1991), which is much lower than the broadly comparable area potash mines and is expected to produce much less subsidence at the surface. Thus, no mine can be said to be truly comparable to the WIPP, but the subsidence data collected from the area potash mines provide some insight into the expected surface subsidence conditions at the WIPP.

Subsidence data have been acquired from some of the area potash mines for use in the analysis and prediction of subsidence at the WIPP. The potash mine data have been used in this report as a benchmark to validate the use of various subsidence prediction methods for

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[2]Numbers are used in this report to refer to the area potash mines due to the proprietary nature of the mine information.

the stratigraphy associated with the WIPP site. The influence function and NCB methods of subsidence prediction have been applied to subsidence measurements taken at one of the area potash mines. Sections 3.3 and 3.4 discuss these benchmarking exercises.

The potash mines of southeastern New Mexico have investigated ground-control problems in the upper Salado Formation for more than 60 years and surface subsidence for more than 40 years. The potash mines have used conventional room and pillar mining, secondary mining where old pillars are removed, and modified long-wall mining methods. Mining techniques used include drilling and blasting, as well as the use of continuous mining machines; mines that have used both techniques report improved ground control with continuous mining.

Large-volume underground mining commonly produces measurable surface subsidence. Within the Carlsbad Potash District, mines have demonstrably caused surface subsidence, resulting in fractures at the surface, ponding, road- and railroad-grade subsidence, and other effects. Some of these effects have been reported; others are well known, if not publicized; and still others may be virtually unknown to the public and to the scientific and engineering community responsible for the WIPP.

The principal mine subsidence data consist of networks or baselines for surface leveling. In 1977, the National Geodetic Survey (NGS) established a baseline over large areas of southeastern New Mexico, including the WIPP site and some potash mines. A resurvey by NGS in 1981 revealed broad changes in elevation. The mine baselines and networks show much larger and rapid responses due to high extraction ratios. Surface subsidence over a panel which has undergone secondary mining can begin within days to weeks and can be generally complete within about two years after the secondary mining ends. Tension within surface rocks, as well as more readily observed subsidence, occurs within an angle of draw of about 35 degrees (measured from the vertical). With more sophisticated leveling (greater accuracy of measurements), the angle of observed effects increases. Data from one of the potash mines, where highly accurate and sensitive surveys were performed, indicate the angle of draw can range from about 45 to nearly 60 degrees.

Precision leveling data, relative to a stable baseline, has been a useful tool for determining movements due to various processes, including subsidence over mined areas. In the Carlsbad area, leveling has been used at varying scales of detail and quality. Unpublished maps and surveys exist for most mines, ranging from a few data points to arrays and lines of varying length and size. At least six mines have conducted some surface-leveling program in conjunction with mining operations. Specific information from these surface-leveling surveys is summarized below for four of the area mines. Data from the other two mines were limited and provided little additional information.

Potash Mine #1. Potash Mine #1 placed a surface network of benchmarks over a panel of modified long-wall mining at a depth of about 210 m (700 ft). The rectangular grid is seven benchmarks long and five wide, with a spacing of about 150 m (500 ft) between benchmarks. The modified long-wall panel area located beneath the network shows small pillars (estimated 2.4 to 3 m [8 to 10 ft] wide and 12 m [40 ft] long), with pillar centers at about 12 m (40 ft) perpendicular to the long wall and 24 m (80 ft) parallel to the long wall. The extraction ratio through these areas is estimated to be about 86 percent (12- by 3-m [40- by 10-ft] pillars) to 89 percent (12- to 2.4-m [40- by 8-ft] pillars). Detailed data for this network have not been provided, and it is not known how detailed or frequent measurements may have been made. While back height is not reported, the surface subsidence here is estimated to be about one-third the back height, assuming the back is 2.4 to 2.6 m (8 to 8.5 ft). From the data provided by the mine, it is not possible to estimate the angle of draw, nor is it possible to determine rates of subsidence.

Potash Mine #2. A limited set of data for Potash Mine #2 was obtained from the BLM (Carlsbad) by permission of the mining company. An undated section of a report describes general conditions and problems associated with mining the third ore zone over areas previous mined in the first ore zone. The first ore zone had been extracted by both primary room and pillar techniques (around 60 percent extraction) and secondary pillar mining, increasing the extraction to 90 percent or more.

Two areas of the mine were monitored for subsidence after secondary mining of the first ore zone. At Area #1, two north-south surface-elevation monitoring lines were established about 180 m (600 ft) apart, with stations about 120 to 150 m (400 or 500 ft) apart. The monitoring lines overlie panel sections about 180 and 240 m (600 and 800 ft) long. From graphic illustrations, subsidence measured approximately one week after completion of mining ranged between 0.3 and 0.6 m (1 and 2 ft) maximum. The angle of draw at the north and south margins of the panel was 25 to 26 degrees.

There are no tabular data presented in support of the graphical illustrations so more exact numbers cannot be reviewed or used in calculations. The data are also limited in time; they apparently only cover the first week after completion of mining. A last concern is that the angle of draw is based only on few stations, and the precision and accuracy of measurements are not known; both can significantly affect the computation of the angle of draw. In view of these concerns, the 25- to 26-degree angle of draw is expected to be a minimum.

The information about Area #2 included a map showing the portion mined, four cross-sections of the panel and surface subsidence; and a surface map with total subsidence contoured. Two cross-sections show subsidence at the western margin of Area #2, along the same line, at two different times. At time 1, surface subsidence was at a maximum of about 1.2 m (4 ft), approximately 210 m (700 ft) east of the western panel margin. The angle of draw at that time was about 9 degrees. At time 2, approximately ten months later, the subsidence at that same point was about 1.5 m (5 ft), and the angle of draw was 28 degrees. The second set of cross sections runs north-south across the southern margin of Area #2. About 90 m (300 ft) north of the panel margin, subsidence was about 0.9 m (3 ft) at time 1, and the angle of draw was about 13 degrees. At time 2, again approximately ten months later, the subsidence was about 1.1 m (3.5 ft), approximately 210 m (700 ft) south of the panel margin and had apparently decreased to about 0.6 m (2 ft) at a distance 90 m (300 ft) south of the panel margin. The angle of draw by that date was 36 degrees. These results were also shown graphically and raise the same concerns as the data from Area #1 above.

Potash Mine #3. Potash Mine #3 has used conventional mining by room and pillar methods and secondary mining in room and pillar areas and is now using a modified long-wall mining system for high extraction ratios under more controlled conditions for mechanical responses of the rock units. Studies at Potash Mine #3 during the 1950s and early 1960s addressed several problems, principally the effects of secondary mining. The mine eventually undertook and still continues long-wall mining techniques that are similar in effects to secondary mining. Surface benchmark lines and networks were established to monitor subsidence effects as secondary mining progressed under an area. This network was supplemented with precise horizontal measurements as well, so that total movement could be monitored. This is the only known example of close monitoring being performed on both vertical and horizontal components of movement over a potash mine within the basin.

Investigation of the surface benchmark lines and networks indicates that the angle, measured from vertical from the mining face to the area of zero tensile strain, ranges from 25 to 34 degrees. The angle to the point where subsidence is measured at 0.6 cm (0.02 ft), ranges from 42 to 55 degrees. The angle to the point where no movement occurs, called here the limiting angle, is difficult to measure and appears to range from about 47 to 58 degrees. Of these angles, the first is defined on the basis of the horizontal measurements of length between hubs to show lengthening (tension) or shortening (compression). The second and third angles depend on good measurements of vertical changes in benchmarks. None of the other studies are truly equivalent to this study at Potash Mine #3; the angle of draw term used for these other studies is in principle the same as the limiting angle used here, but the measurements are not known to be equivalent in quality to those performed at Potash Mine #3.

Consultants for Potash Mine #3 determined the history of both the horizontal strain and vertical strain relative to the mining front as it advances. Above the mining front is an area of tensile strain, as measured by horizontal distances between benchmarks. The area of tension can range from a short distance in front of the mining face to an area behind the mining face. The maximum tension for a face adjacent to unmined territory, as would be the case with much of WIPP, was slightly behind (on the mined side) of the mining face. The vertical angle of the point of maximum tension, measured from the mined face that was adjacent to unmined territory, was −3 degrees. The consultants also noted a slight uplift along some baselines in advance of the mining front. The area just inside the mining front goes from tension to a point of maximum compression. Through this area of maximum compression, subsidence of the surface is rapidly taking place soon after mining, adjusting with time to a steadier and lesser rate. Most settlement over these areas of high extraction by secondary mining took place within two years after completion of the mining, with only slight adjustments of most benchmarks after that.

Potash Mine #4. The data now available from Potash Mine #4 consist of a small surface network (15 benchmarks) over a panel second-mined over a three-month period. Network benchmark elevations were measured four times after secondary mining over a period of about 19 months. The panel is about 370 m (1,200 ft) below the surface, and the panel height averages 2.6 m (8.5 ft). Adjacent panels have subsequently undergone secondary mining as well, and benchmarks are being established over the panel to the east of this panel. No data are available at this time from this adjacent panel, as the network is being measured.

The data provided were entered into a database table, and the relative subsidence for each benchmark and each date was calculated. In addition, the relative movement from date to date was established for each benchmark. These data were plotted on maps, and preliminary contours of subsidence were drawn. The data calculations and contours display several features to be noted:

- Several benchmarks around the perimeter of the network and second-pass mining area were calculated to have risen during later months.
- Maximum subsidence measured at the center of the panel through this 19-month period is about 0.4 m (1.35 ft).
- More than half the measured subsidence at the panel center occurred within weeks of the end of mining, and the rate of subsidence decreased thereafter.

The maximum subsidence measured throughout the period represents about 16 percent (1.35/8.5) of the panel height. This is much less than over some other mine areas. The differences could be due to unmeasured subsidence, which has occurred since the last set of measurements; differences in geology; or other, undetermined factors.

Graphically estimated angles of draw range from about 29 to 32 degrees up to 43 to 46 degrees, depending on which surface benchmarks are included. The lower range, 29 to 32 degrees, would be considered minimum angle, while the upper range of 43 to 46 degrees would be considered the maximum angle.

Summary of Potash Mine Subsidence Data. There exist considerable experience and data within the potash industry about ground control and subsidence in southeastern New Mexico. While some of this information may not correspond directly to the conditions for WIPP, it can be used for test problems or validation problems for subsidence prediction models at the WIPP. The data from the four area potash mines are summarized in Table 2-1. Based on the data, the ranges for key parameters are as follows:

- The range of total subsidence at the area potash mines is from 0.4 to 1.5 m (1.3 to 5 ft), representing 16 to 66 percent of initial excavation height.
- The observed angle of draw from the vertical at the edge of the underground excavation ranges from 25 to 58 degrees.

Surficial Features. If fracturing connects from the mining horizon upward to water-bearing units or the surface, pathways could be created that would allow water to enter the workings. Of the potash mines in southeastern New Mexico, two are reported to have had brine inflows to underground panels that were greater than the minor seeps or weeps common in the area. There is no known evidence at this time that these brines are connected to inflow from the surface or near-surface units.

The data obtained from the potash mines also provide the best available information about surface strain. The surface-strain information may be helpful in understanding hydrological responses to subsidence produced by natural processes or by mining. Maximum strain at the surface, measured by horizontal changes between benchmarks over the panels of one potash mine, is generally less than 1 percent and is commonly about 0.5 percent. The strain is expressed as uplift and subsidence and also as surface fractures, ranging from hairline cracks to significant separations. These fractures, either hairline or with significant separation, are presently observed over various portions of mines within the basin. These fractures are surface features and do not necessarily indicate fracturing within the rock mass. Horizontal strain is expected to be more subtle at WIPP due to the lesser degree of predicted total subsidence.

Table 2-1

Summary of Subsidence Parameters from Area Potash Mines[a]

Location	Excavation Depth (m)	Maximum Subsidence Observed[b] (m)	Percent of Excavation Height[c]	Angle of Draw[d] (degrees)
Potash Mine #1	210	0.8	33%[e]	NA
Potash Mine #2				
Area #1	300	0.6	24%[e]	25 to 26
Area #2	300	1.1 to 1.5	40 to 60%[e]	36
Potash Mine #3	300	1.5	66%	47 to 58
Potash Mine #4	370	0.4	16%	29 to 46

[a]All values taken from Powers, D.W., 1993, "Background Report on Subsidence studies for the Potash Mines and WIPP Site Area, Southeastern New Mexico," consultant's report for IT Corporation, Albuquerque, New Mexico.

[b]Maximum subsidence observed represents the maximum vertical displacement observed at the surface during the observation period. Observation periods ranged from one week to greater than one year. The maximum surface subsidence observed during this observation period is probably less than the total surface subsidence that can be expected over the excavated area.

[c]Percent of excavation height is calculated as the maximum subsidence observed divided by the excavation height.

[d]The angle of draw is the angle between the vertical and the line passing through the edge of the underground excavation to the edge of the observed surface subsidence.

[e]The excavation height used to calculate percent of excavation was estimated at 2.6 m (8.5 ft), based on the typical excavation height in the potash mines.

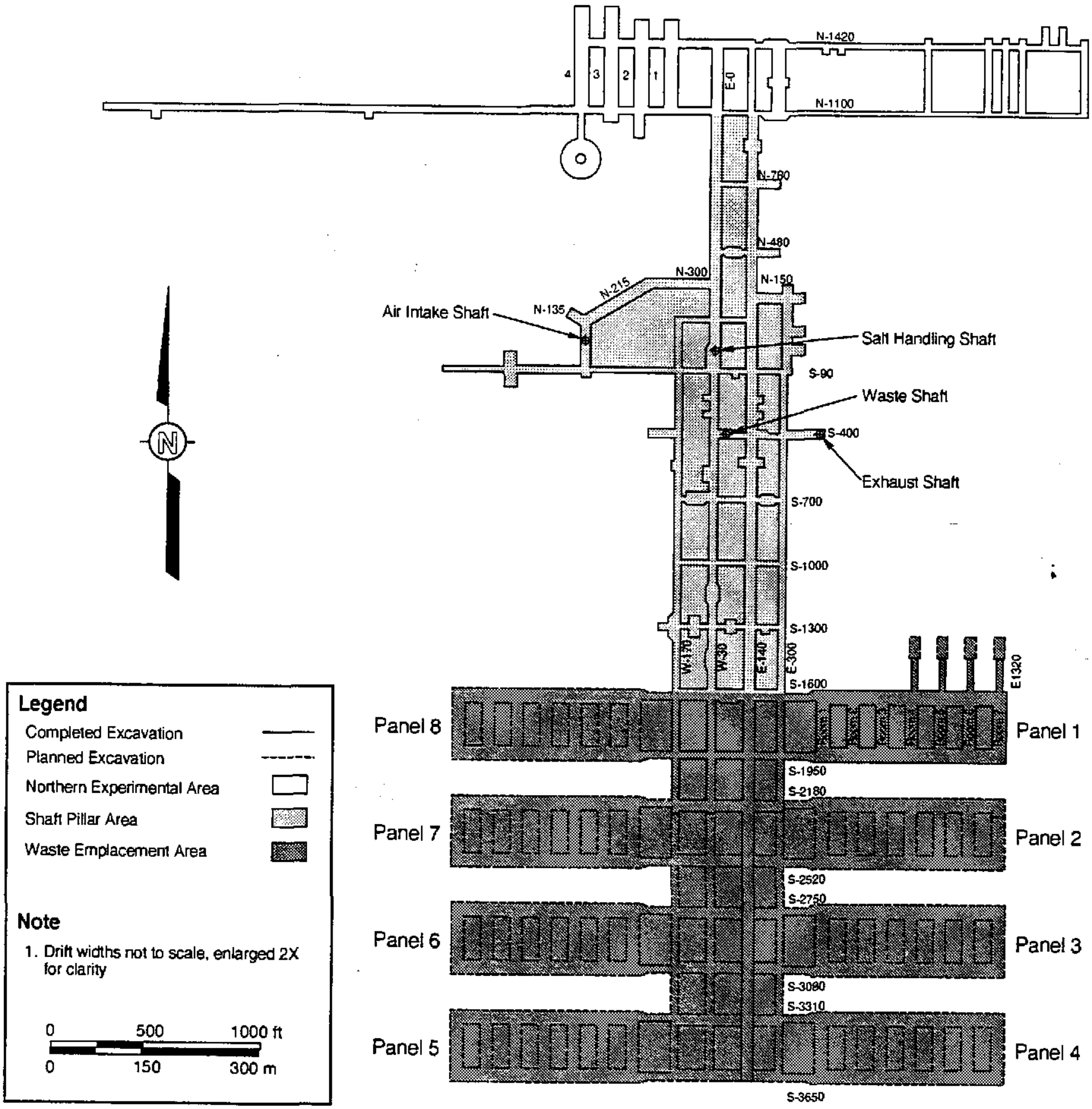

Figure 2-1
Repository Areas for Backfill Consideration at the WIPP

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3.0 Estimation of the Geomechanical Effect of Backfill at the WIPP

This chapter presents calculational and computer modeling approaches that were performed to help determine the geomechanical effect of backfill on areas within the WIPP underground facility. Observations and geotechnical data collected at the WIPP site are investigated to see if they can be used to estimate expected responses and interactions of the underground workings. How backfill will affect these responses and interactions is also discussed. The mass conservation calculation and influence function method are used to estimate the amount of subsidence expected from the underground excavations with and without backfill.

This chapter also describes the NCB method for analysis of subsidence. Included in this discussion is the applicability of the NCB method to the WIPP site stratigraphy and mining technique. The NCB method is first applied to an area potash mine, and the results are then compared to the actual measurements made. The high degree of correlation indicates that this method is applicable to the WIPP underground workings. The results of the NCB subsidence calculations on the WIPP geometry and stratigraphy are also presented.

A detailed description of the numerical modeling using the FLAC code (Itasca, 1991) is given in Section 3.5. FLAC is a finite difference code used to calculate stress, strain, and displacements around modeled excavations, and is used to calculate the degree of subsidence at the surface and the interaction of the backfill material with the surrounding intact rock. An explanation of the computer code is included.

3.1 Data and Data Sources

This chapter presents the results of several different methods for predicting surface subsidence and ground reaction as a result of underground excavation. Whenever possible, consistent data were used across the various subsidence prediction methods to allow for the best comparison of calculational and modeling results. Table 3-1 presents the input data and assumptions used in the subsidence prediction calculations and FLAC modeling performed for this report.

3.2 Room Interaction Estimates Based on Observations and Geotechnical Data

Geotechnical data has been previously collected in the WIPP underground to subjectively estimate future ground reactions around the excavations. The types of geotechnical data available for the underground include horizontal and vertical convergence measurements, observations of fracture development in the floor and back, and ground-penetrating radar (GPR) surveys. Since no major portions of the WIPP underground have been backfilled, underground observations and geotechnical data are not available to directly assess the geotechnical effects of backfill emplacement on the underground excavations. (Small scale backfill emplacement demonstrations have been performed in one of the alcove entries in Panel 1.) The geotechnical information available for the surface area over the underground workings is also limited. Baseline leveling surveys were performed in 1977 and 1981 (Powers, 1993) prior to the start of excavation at the WIPP.

3.2.1 Convergence Measurements

Convergence is the measured amount of closure between the roof and the floor or the walls of an excavation due to creep closure. Convergence rate is the amount of closure relative to time. Convergence data have been collected in the WIPP underground since the excavation of the first access drifts. Horizontal and vertical convergence data are compiled in the annual geotechnical field data and analysis reports. These reports present the data recorded from convergence meters, borehole extensometers, strain gages, and stress meters that have been installed throughout the underground excavations. Convergence measurements are evaluated as a primary means of identifying excavation areas where ground conditions may be deteriorating. Convergence data and convergence rates may provide some information of the interaction of nearby or adjacent excavations.

Review of the data indicates that, in some locations, intersecting excavations can have an accelerating effect on the convergence rates, possibly resulting in an adverse effect on the excavation stability. In other locations, intersecting excavations may have an advantageous effect to the excavation stability, exhibited by a lower convergence rate. The only conclusion that can be drawn from these observations and comparisons is that no trend exists. Each location must be considered individually, and no apparent correlation exists between the long-term roof-to-floor convergence rate and the relative proximity of other excavations.

3.2.2 Ground-Penetrating Radar Surveys

GPR surveys have been performed at various locations in the WIPP underground (DOE, 1990d; DOE, 1991a; Kannenberg, 1991; Milligan, 1993). These previous GPR surveys have been used to investigate the occurrence and extent of fracture propagation near and around excavations. The results of GPR surveys that have been performed in isolated drifts and drifts located in areas of multiple excavations were compared to assist in determining the effect of excavations on adjacent excavations.

Based upon the comparisons, it is evident that fracturing of the floor and specifically of Marker Bed 139 (MB139) occurs fairly quickly after excavation, probably between 10 months and 25 to 28 months based on the observations presented above. Because of this rapid progression of fracturing in the floor and MB139, the emplacement of backfill materials in rooms or access drifts will not prevent or significantly reduce the onset or propagation of this fracturing. A crushed salt backfill material would take too long to reconsolidate and provide the necessary resistance to the surrounding stresses to prevent the fracturing of MB139 even if it could be emplaced immediately after excavation.

3.2.3 Fracture Development

Borehole inspections of fracturing and bed separation have been the most successful method for determining the condition of the rock immediately surrounding excavations at WIPP. Fracture logging of open boreholes has been done on an informal basis since the first holes were drilled at the facility horizon in 1983 (Francke and Terrill, 1993). The Excavation Effects Program (EEP) was initiated in 1986 after the discovery of a large fracture system in SPDV Test Room 3. The purpose of the EEP is to study fractures that develop as a result of underground excavation at the WIPP and to provide consistent documentation and monitoring of those fractures. Arrays of boreholes were drilled at 36 locations around the underground. Six arrays are located in intersections and thirteen arrays are located in high-extraction areas. Two conclusions pertinent to backfill and room interaction have been derived from the eight years of observations of the boreholes (Francke and Terrill, 1993). First, EEP showed that the geometry of fracture patterns around excavations is uniform throughout the EEP arrays. Because about half of the arrays are located in intersections or high extraction areas, it can be further concluded that room interactions do not significantly affect the distribution of fractures around WIPP excavations. The second conclusion from the original EEP data was that the rate of fracture development depends primarily on the drift size and not on extraction ratio or room interactions.

In summary, the EEP data from the WIPP underground indicate that fracture formation, and therefore excavation stability, is not significantly affected by extraction ratio or room interactions. That is not to say that room interactions do not occur. It is possible that the location of SPDV Room 1 in the SPDV panel and the proximity of the E140 drift to Panel 1 led to accelerated deterioration of those drifts. However, it is quite likely that these effects are most pronounced immediately following excavation, when stresses and displacement rates are high, and diminish with time, as stresses redistribute. In that case, backfill emplaced five to ten years after excavation would not significantly alter the final condition.

3.3 Mass Conservation and Influence Function Analyses of Subsidence

The basic aim of the mass conservation calculation and influence function method are to provide an accurate assessment of subsidence. The mass conservation calculation yields an estimate of the maximum expected subsidence, based on the principle that the expected subsidence is a function of the dimensions of the workings and therefore is directly proportional to the seam height and the extraction ratio. Also, a fundamental assumption held for both methods is that the surface subsidence cannot exceed the extracted seam height. Both methods assume 100 percent of the subsidence has occurred. The methods do not consider time dependency. The influence function method is based on many of the same assumptions as the mass conservation calculation. The influence function method also provides a profile of the expected shape of the subsidence trough and the lateral extent of influence on the surface of the subsidence.

The mass conservation calculation and the influence function method are discussed in the following sections. The effects of open or backfilled excavations in the different areas of the WIPP underground are studied, and the results are compared.

3.3.1 Mass Conservation Predictions

The mass conservation calculation assumes that the volume of subsidence is directly proportional to the volume of the openings. Therefore, the range of expected maximum subsidence will be logically upper-bounded by the height of the underground workings. This calculation does not account for any swelling of the overlying strata during the subsidence. However, this upper bound is rarely reached, and the expected maximum subsidence is calculated using a subsidence factor, which has a maximum value of 1. The subsidence factor is dimensionless and is dependent on the dimensions of the pillars and chambers and is, therefore, equivalent to the local extraction ratio of the excavation (Kratzsch, 1983). The following expression is the calculational base for maximum subsidence in the mass conservation calculation as well as for the influence function method (Kratzsch, 1983):

$$S_{\max} = a\ M \tag{3.1}$$

where

S_{max} = Maximum value of subsidence
a = Extraction ratio (area excavated/area enclosed)
M = Height of the underground opening.

In order to perform the subsidence calculations for the WIPP site, the three areas described in Section 2.1.3 will be studied separately, namely, the waste emplacement area, the shaft pillar area, and the northern experimental area. The mass conservation calculation is applied based on the values for excavated and enclosed areas presented in Table 3-2 (from SNL/NM, 1991).

Using the values of extraction ratio and average excavation height of the empty openings (Table 3-3) in Equation 3.1, the values of maximum final subsidence for each of the three study areas are calculated. Table 3-3 presents the results of this calculation for each area. These maximum final surface subsidence predictions are for the no-backfill scenario. The maximum subsidence predicted for each of the three underground areas ranges from 0.24 m (9.4 in.) in the northern experimental area to 0.28 m (11.0 in.) in the shaft pillar area to 0.86 m (33.9 in.) in the waste emplacement area, assuming no CH-TRU waste in that area.

For the scenario of backfill being placed in the excavations, the calculation is similar, except that the excavation height is reduced to reflect the amount of solid backfill material placed in the openings. The total surface subsidence is then a function of the initial excavation height, the local area extraction ratio, and the porosity of the material that is placed in the excavation. In calculating the expected subsidence, the amount of horizontal and vertical room convergence that occurs between the time of excavation and backfill emplacement is ignored (i.e., the volume of backfill placed in an excavation is based on the original excavated dimensions of the opening).

The porosity of crushed salt backfill material that could be placed in the northern experimental area and the shaft pillar area is assumed to range between 21 and 44 percent (Section 3.1). The end points of this range represent a loosely placed backfill material and a well-compacted backfill material. It is assumed that the final porosity of the backfill material after being consolidated to lithostatic pressure will be less than 1 percent (similar to the porosity of intact salt). Table 3-3 provides the results of the mass conservation subsidence estimate for the northern experimental area and the shaft pillar area for the high- (i.e., loose) and low-porosity (i.e., compacted) backfill material. This calculation indicates the maximum subsidence in the northern experimental area, with loose and compacted backfill materials ranges from 0.11 to 0.05 m (4.3 to 2 in.), respectively. The maximum subsidence calculated for the shaft pillar area with loose and compacted backfill materials ranges from 0.12 to 0.06 m (4.7 to 2.4 in.), respectively.

If only CH-TRU waste drums are placed in the waste emplacement area, the calculated maximum surface subsidence expected is 0.62 m (24.4 in.) (Table 3-3). This calculation is based on a packing configuration of waste drum seven packs presented by SNL/NM (1991). Because of the high average initial porosity of the waste, the waste does not significantly reduce the maximum expected surface subsidence over the waste emplacement area. The initial average porosity of the CH-TRU waste drums is 76.5 percent, and the final average porosity at the assumed lithostatic pressure (14.8 Megapascals [MPa]) is 18.6 percent (Butcher and Mendenhall, 1993). The total change in porosity is 58 percent, indicating a large decrease in waste volume during room closure. Adding the void volume that exists above the waste stack yields an equivalent room porosity of 72 percent.

The calculated maximum surface subsidence for the waste emplacement area with CH-TRU waste and crushed salt backfill ranges from 0.52 to 0.55 m (20.5 to 21.7 in.) (Table 3-3). This calculation is based on an initial equivalent room porosity of 61 to 64 percent for the waste and backfill composite, assuming a 0.71-m (2.3-ft) ventilation air gap above the waste and backfill and compacted and loose crushed salt backfill material, respectively (DOE, 1991b). This is approximately a 16 percent reduction in total subsidence (0.62 to 0.52 m [24.4 to 20.5 in.]) for the respective cases, with and without backfill placed over the waste drums.

3.3.2 Influence Function Predictions

The basic principle of the influence function method is the application of the law of superposition to determine the overall influence of an extraction area when divided into infinitesimal parts. This method is based on the assumption that each point in an underground excavation has a circular region of influence on the subsidence at the surface around that point. Therefore, in an underground opening, neighboring extraction elements generate identical subsidence basins at the surface, and by superimposing the influence of all extraction elements, it becomes possible to calculate the total subsidence of a given point at the surface. The area of influence is determined by the limit angle (Figure 3-1). The circle is centered on the surface point, and its radius is given by the following equation (Kratzsch, 1983):

$$R = H \cot(\gamma) \tag{3.2}$$

where

R = Radius of the influence area
H = Depth of the excavations
γ = Limit angle from the horizontal (see Figure 3-1).

This area is also called the critical area—the depressed area in which maximum subsidence is reached only at one single point. The percentage of underground workings enclosed in this circular area will determine the influence that the openings have on the center of the critical area. Every opening will have a weight in the total influence factor of that particular point. Excavations located near the center of the circle will have more weight on the total percentage than the excavations located near the outer limits of the circle. The addition of all the excavation influences within the circle will yield the final percentage of influence on that point. This value is also called the influence factor, and the product of this factor and the maximum calculated subsidence (from the mass conservation calculation) yields the predicted subsidence at that particular surface point.

The graphical method to calculate influence factors is also called the integration grid method. This method has been applied to room and pillar workings in rock salt similar to the WIPP site (Kratzsch, 1983) and has also been used in computer simulations (Steed et al., 1985). In order to verify the applicability of the integration grid method to the WIPP workings, two actual subsidence profiles from a potash mine in the Carlsbad area were studied, and the results of the integration grid method were compared with the actual field data.

3.3.2.1 Graphical Influence Function Analysis of Area Potash Mine

The graphical influence function method was used to estimate the surface subsidence over two different panels at a potash mine near WIPP. The potash mine excavation dimensions, depth, and extraction ratio were provided by Powers (1993). Figures 3-2 and 3-3 show the general layout of the excavated panels. The mined seam height is 2.13 m (7.0 ft) for Profile A and 3.8 m (12.5 ft) for Profile B. The depth at both profiles is 305 m (1,000 ft).

The limit angle from the horizontal is assumed to be 60 degrees, based on data provided by surface-leveling surveys performed by the potash mine operators (Powers, 1993).

The influence function circle (or critical area) for the underground workings of the potash mine is calculated from Equation 3.2 as follows:

Depth below surface workings, H = 305 m (1,000 ft)
Limit angle from the horizontal, γ = 60 degrees.

Thus,

R = (305 m) cot (60°) = 176.1 m (578 ft).

The radius of 176.1 m (578 ft) was then divided in three equal segments that were used to draw three concentric circles. The area within each circle, or ring, has a 100/3 or 33.3 percent influence on the total subsidence at the center of the circles. Using a computer-aided drawing system, the influence function circle was superimposed along the profile on a scaled layout of the underground excavation. The center of the influence function circle is placed on the different nodes along the profile line that dissects the workings (see Figures 3-2 and 3-3). For each of these nodes, an influence factor is calculated. The influence factors calculated for each node across the potash mine profile in Figure 3-3 (Profile B) are presented in Table 3-4.

Field measurements of subsidence from the potash mine were used to evaluate the accuracy of the influence function method as applied to the stratigraphy in the area of the WIPP site. It is assumed that maximum subsidence was almost reached when the field data were taken. The predicted subsidence profiles across the potash mine panels are presented in Figure 3-4. Figure 3-4 also presents the shape of the subsidence basin observed using the field measurements. The calculated subsidence along Profile A substantially differs from the actual field data by overestimating the amount of subsidence that was observed. However, this profile is located in the corner area of the mined area, which could limit the amount of observed subsidence. Profile B is in better agreement, with the maximum predicted subsidence (3.16 m [10.4 ft]) being slightly greater than the maximum observed surface subsidence (2.80 m [9.2 ft]). The difference between observed and predicted surface subsidence may also indicate that subsidence activity is not yet complete. Because of the good agreement in subsidence profile and maximum subsidence between the influence function method and the field observations, the influence function method is expected to give reliable predictions of total surface subsidence over the WIPP.

3.3.2.2 Graphical Influence Function Analysis of the WIPP

This section presents the use of the graphical influence function method for the WIPP site underground layout. Using a depth of 644 m (2,115 ft) for the WIPP underground and a limit angle of 60 degrees in Equation 3.2, the radius of the influence circle is calculated to be 371.8 m (1,219.8 ft). As before, the radius (371.8 m) is then divided in three equal segments, creating three concentric rings, each having a 33.3 percent influence on the total subsidence at the center of the circles. The influence circle is placed over each of the different nodes of the regular grid overlaying a scale drawing of the WIPP underground (Figure 3-5). The influence factor is calculated graphically for each node of the grid. As a result of this calculation, a layout of the subsidence influence factors at the surface level is obtained (Figure 3-5). The values of the total maximum subsidence for each of the three major underground areas of the WIPP are calculated using the mass conservation calculation described in Section 3.3.1, multiplied by the greatest influence factor in each area. The results of these calculations are presented in Table 3-5. When the influence factors are multiplied by the maximum expected subsidence for a particular WIPP underground area and backfilling option, a layout of the expected subsidence is obtained. Figure 3-6 presents the predicted subsidence profile for the case of no backfill in any of the underground areas, and Figure 3-7 presents the predicted subsidence profile for the case of compacted backfill in all of the underground areas.[3]

3.3.3 Summary of Results

The previous calculations are based on the assumption that full closure occurs and that the closure of the rooms is entirely transmitted to the surface. Due to the viscoplastic nature of rock salt, it is reasonable to assume complete closure with time. It is uncertain whether the closure will be entirely transmitted to the surface.

Using the mass conservation calculation, the maximum expected subsidence for each backfilling option is summarized in Table 3-3 for each of the three WIPP underground areas. The maximum expected subsidence for the waste emplacement area is 0.62 m (24.4 in.), assuming the panels are filled with untreated CH-TRU waste drums. The reduction in subsidence in the waste emplacement area due to the placement of crushed rock salt backfill

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[3]Both cases include untreated CH-TRU waste drums in the waste emplacement area.

is between 0.07 and 0.10 m (2.8 and 3.9 in.). The amount of subsidence in the waste emplacement area is largely dependent on the high porosity of the CH-TRU waste drums, which occupy most of the volume.

The maximum expected subsidence for the northern experimental area, based on the mass conservation estimates, is 0.24 m (9.4 in.), assuming no backfill, and 0.05 m (2.0 in.), assuming the emplacement of a compacted crushed salt backfill immediately after excavation. The maximum expected subsidence for the shaft pillar area is 0.28 m (11.0 in.), assuming no backfill, and 0.06 m (2.4 in.), assuming compacted crushed salt backfill emplaced immediately after excavation. Any delay in backfill emplacement diminishes any effect the backfill may have.

The maximum expected subsidence from the influence function method for each backfill option is summarized in Table 3-5. The results are much less than the results of the mass conservation calculation. The small overall size of the WIPP excavated area, relative to the depth and the angle of draw, make the WIPP underground "sub-critical" (i.e., the middle of the subsidence trough does not reach the maximum expected subsidence calculated by Equation 3.1). The maximum expected subsidence in the waste emplacement area with waste and no backfill (waste only) is 0.40 m (15.7 in.), with waste and loose backfill is 0.36 m (14.2 in.), and with waste and compacted backfill is 0.34 m (13.4 in.). The maximum expected subsidence in the shaft pillar area without backfill is 0.10 m (3.9 in.), with loose backfill is 0.04 m (1.6 in.), and with compacted backfill is 0.02 m (0.8 in.). The expected subsidence in the northern experimental area without backfill is 0.08 m (3.1 in.), with loose backfill is 0.04 m (1.6 in.), and with compacted backfill is 0.02 m (0.8 in.).

3.4 Empirical Analysis of Subsidence

There are many empirically derived relationships for predicting subsidence. The majority of these relationships have been developed from observed surface subsidence behavior, and consequently, they apply specifically to the ground and mining conditions that prevailed at the time the observations were made. Empirically derived relationships rely on a number of observations and case studies sufficiently large enough to establish levels of accuracy for prediction of anticipated mining subsidence. The best known of the empirically derived relationships is presented in the NCB Subsidence Engineers' Handbook (NCB, 1975). The NCB developed an extensive program of scientific study and investigation of coal mining subsidence in the United Kingdom during the period from 1950 to 1965. Field investigations were set up, and detailed measurements were made of subsidence, lateral displacement, ground strains, and tilt in many different mining and geological conditions. In addition, comparisons were made between British and German experiences, knowledge, and observations of mining subsidence. This work laid the foundation for the modern understanding of ground movement due to mining subsidence, and the collection of these field observations ultimately resulted in the NCB subsidence prediction method, which is used worldwide (Whittaker and Reddish, 1989).

The NCB empirical method model consists essentially of a series of tables of data, charts, and graphs from which subsidence data can be derived and which relate to specific mining situations. Graphs are presented to provide correction factors for these specific mining conditions, such as length of the panel, pillar size between panels, and time since excavation. The general geological conditions are not considered as an individual parameter, since most of the observations relate to similar overburden (Whittaker and Reddish, 1989).

3.4.1 Application of the NCB Method to a WIPP Area Potash Mine

The NCB method is an empirical method based on case histories of coal mining in the United Kingdom. In order to verify the applicability of the method to the particular stratigraphy found near the WIPP site, the NCB method was first applied to one of the potash mines located near the WIPP site. Field measurements of actual subsidence were compared to the predicted subsidence to determine the accuracy and applicability of the NCB subsidence prediction method for the geologic conditions found at or near the WIPP site. The potash mine excavation and subsidence data that were used are the same data that were used in verifying the applicability of the influence function method (Section 3.3.1).

Two profiles representing two different mining methods were used to check the applicability of NCB method calculations to mining in the WIPP area. Both methods were applied at the same mine. The first profile, Profile A, represents a modified long-wall mining operation, with an extraction ratio as high as 0.92 (Powers, 1993). The second profile, Profile B, represents a room-and-pillar configuration, with an extraction ratio of 0.83 (Powers, 1993). A brief summary of the method used to determine the surface subsidence prediction for each of these two profiles follows.

Profile A. For the estimation of surface subsidence using the NCB method along Profile A (see Figure 3-2), the depth of the underground workings was 305 m (1,000 ft), the panel width was 457 m (1,500 ft), the height of the opening was 2.13 m (7.0 ft), and the extraction ratio was 0.92 (Powers, 1993). For this application of the NCB method, any unexcavated area or pillars were ignored, and all of the underground workings were treated as a single panel. To do this, an "equivalent seam height" for the panel was calculated by multiplying the height of the opening by the extraction ratio:

Equivalent seam height = 2.13 m * 0.92 = 1.96 m (6.4 ft).

The maximum subsidence was calculated by multiplying the equivalent seam height by the subsidence factor. The subsidence factor, 0.88 in this case, was taken from a graph provided in the NCB Subsidence Engineers' Handbook (NCB, 1975) and was based on the depth and width of the mined panel. The maximum subsidence used was:

Maximum subsidence = 0.88 * 1.96 m = 1.72 m (5.6 ft).

The difference between this predicted value of surface subsidence and the actual field measurements was 0.04 m (1.6 in.) (1.72 m versus 1.68 m [5.6 versus 5.5 ft]). This difference represents an error of less than 3 percent. The shape of the subsidence profile was predicted using factors provided in the NCB Subsidence Engineers' Handbook (NCB, 1975). Figure 3-8a presents a comparison of the predicted and actual subsidence profile for Profile A.

Horizontal strain associated with surface subsidence can also be estimated using the NCB (1975) method. The predicted and actual measured horizontal strains for Profile A are presented in Figure 3-8b.

Profile B. The predicted surface subsidence and horizontal strain are calculated for Profile B (Figure 3-3) in the same manner as described above for Profile A. The depth of the underground workings used in the calculations was 305 m (1,000 ft), the width was 945 m (3,100 ft), the height of the opening was 3.81 m (12.5 ft), and the extraction ratio was 0.83. The equivalent seam height was calculated to be 3.16 m (10.4 ft). The subsidence factor from the NCB method was 0.95 for this profile, because of the greater width of the excavation. The maximum surface subsidence was estimated to be 3.00 m (9.8 ft), which was 0.2 m (7.9 in.) greater than the actual surface subsidence observed along Profile B. The predicted and actual surface subsidence profiles are presented in Figure 3-9a. Similarly, the predicted and actual horizontal strains along Profile B are presented in Figure 3-9b.

Based on the results of the calculations presented above, the NCB subsidence prediction method appears to be a suitable tool for estimating total surface subsidence and horizontal strain at excavations with high extraction ratios in the stratigraphy near the WIPP site. The NCB method approximates with a 7 percent error to the maximum reported subsidence for the room-and-pillar workings (Profile B) and within a 3 percent error to the modified long-wall workings (Profile A). It should be noted that the WIPP has a much lower extraction ratio than the potash mines. It is uncertain what effect, if any, this may have on the accuracy of the NCB method subsidence predictions at WIPP.

3.4.2 Application of the NCB Method to the WIPP Underground

The NCB method was applied to each of the three areas of the WIPP underground. The subsidence basin shape and magnitude for each underground area was calculated, and the superposition of the different basins yielded the final expected subsidence for the entire facility.

To evaluate the different possible backfill scenarios, the three WIPP underground areas were studied separately, and the effect of backfill used in each area was analyzed. In the northern experimental and shaft pillar areas, two possible cases were considered: 1) leaving the excavations empty with no backfill material and 2) backfilling the excavations from floor to roof with crushed salt backfill. In the waste emplacement area, since leaving the rooms empty was not a reasonable situation, the two cases were assumed to be: 1) filling the waste rooms and access drifts with untreated CH-TRU waste drums without backfill and 2) filling the waste rooms and access drifts with untreated CH-TRU waste drums and backfill material placed over and around the waste stacks.

Different compaction densities for the crushed salt backfill material were considered in this study, and a range of densities/porosities was assumed, based on existing literature on crushed salt consolidation. The maximum dry density of crushed salt backfill material used was 1.82 g/cm^3 (114 lb/ft^3), with a corresponding porosity of 21 percent (Valdivia, 1994). The minimum dry density of crushed salt backfill material with no compaction was 1.28 g/cm^3 (80 lb/ft^3), with a corresponding porosity of 44 percent (Holcomb and Hannum, 1982). Both studies used similar grain-size distributions. Valdivia used a 6.5 percent water content and compaction effort equivalent to the modified Proctor test (ASTM, 1978), whereas Holcomb and Hannum (1982) used a 0.5 percent water content and no compaction effort. These two values were assumed to be practical limits for the range of possible backfill placement densities and porosities.

To calculate the maximum subsidence expected over the three WIPP underground areas, the mass conservation calculation and influence function analysis approaches, as described in Section 3.3, were used. Using the same extraction ratios and average excavation heights as used in the mass conservation calculation (Table 3-3), the maximum expected subsidence for each area was determined assuming no backfill material. The complete results of these calculations for each area are provided in Table 3-6.

The maximum expected subsidence was recalculated for the case of high-porosity loose backfill placed in each of the three underground areas. As with the previous prediction methods, the backfill was assumed to be placed from floor to roof, with no gap above the backfill. It was also assumed that the backfill was placed into excavations immediately after excavation and that no convergence had occurred in the excavations. This assumption provided an overestimate of the total reduction in subsidence that could occur due to backfilling. The results of the loose backfill scenario for each underground area are presented in Table 3-6.

The maximum expected subsidence was recalculated for the case of the low-porosity compacted backfill placed in each of the three WIPP study areas. The results of these calculations are also presented in Table 3-6.

The shape of the subsidence profiles for the scenario of no backfill across the northern experimental area and the shaft pillar area were calculated using the NCB method graphs (see Figures 3-10a and 3-11a, respectively). The horizontal strains across these profiles are presented in Figures 3-10b and 3-11b. The subsidence profile and horizontal strain profiles for the expected subsidence over the waste emplacement area, assuming untreated CH-TRU waste only, are presented in Figure 3-12. Figures 3-13, 3-14, and 3-15 present the expected subsidence and horizontal strain profiles for the northern experimental area, shaft pillar area, and waste emplacement area respectively, for the scenario of loose crushed salt backfill. Figures 3-16, 3-17, and 3-18 present the expected subsidence profiles and horizontal strains for each of the areas for the scenario of a compacted crushed salt backfill. By superimposing the expected subsidence profiles for each of the three WIPP underground areas and extrapolating the results using methods prescribed by the NCB method, three-dimensional representations of the expected maximum subsidence above the entire WIPP site were generated for the various backfilling scenarios. Figures 3-19 through 3-21 present the contour plots representing the subsidence of the WIPP site for the cases of no backfill in any area, loose backfill placed in each area, and compacted backfill placed in each area. Figure 3-22 presents the case of no backfill in the waste emplacement area and compacted backfill in the rest of the WIPP underground.

3.4.3 Summary of NCB Analysis Results

The NCB method has been used extensively throughout the world to predict surface subsidence in the coal mining industry. However, in order to assure the applicability of the method to the evaporite mine workings in the vicinity of WIPP, a verification problem was studied. Two case histories from a potash mine in the WIPP vicinity were analyzed. The case histories were representative of two different mining situations: long-wall and room-and-pillar mining. The results showed that the NCB method fits within a maximum error of 7 percent of the actual subsidence profiles. The accuracy of the results in the verification problem indicates that the NCB method can be reasonably applied to potash mining operations near WIPP. Even though the WIPP has a much lower extraction ratio than the potash mines, it is assumed that the NCB method is also applicable to the WIPP site.

The NCB analysis of the WIPP site reveals that maximum expected subsidence would occur above the waste emplacement area. The maximum expected subsidence (0.53 m [20.9 in.]), assuming no backfill emplacement, would be reduced by 0.09 m (3.5 in.) if a well-compacted, crushed rock salt were used as backfill surrounding the waste. The emplacement of backfill in the waste emplacement area has only a minor influence on reducing subsidence, due to the fact that the greatest part of the waste rooms is filled with a very porous waste, with initial porosities of approximately 76.5 percent (Butcher and Mendenhall, 1993). Consequently, the influence of backfill is proportional to its volume, and this is constrained by the purpose of the waste disposal facility, which is to dispose of the maximum volume of waste.

The maximum expected surface subsidence in the northern experimental area and the shaft pillar area is minimal (0.02 and 0.04 m [0.8 and 1.6 in.], respectively) based on the NCB analysis of these areas. This could be reduced to less than 0.01 m (0.4 in.) if a compacted backfill were placed in these areas. The predicted subsidence values for each area and backfill scenario are summarized in Table 3-6.

Maximum predicted horizontal strains at the surface for the case of no backfill range from a low of 0.0084 percent in the northern experimental area to a high of 0.053 percent along the boundary of the waste emplacement area. Horizontal strains observed at the potash mines (which are comparatively shallower) in the vicinity of the WIPP site range from 0.37 to 0.62 percent. The predicted horizontal strain values for each WIPP area under each backfill scenario are summarized in Table 3-7.

3.5 FLAC Modeling of the WIPP Underground

Numerical modeling is considered one of the better methods available for quantifying the rock mechanical effects of backfill. Therefore, a series of models have been developed for this report specifically to determine the following:

- The maximum subsidence (vertical displacement) that can be expected at the surface
- The effect of backfill on underground stability
- The shape, lateral extent, and magnitude of the potential subsidence trough at the surface and at selected levels above the underground facility.

This section discusses the code used, describes the models, and presents results.

3.5.1 The FLAC Code

FLAC software has been used to develop numerical models of the underground excavations at the WIPP since 1991. FLAC is a two-dimensional explicit finite difference code that simulates the behavior of rock and soil-like structures. The WIPP Reference Creep Law is built into FLAC and has been verified to Nuclear Regulatory Commission standards (Itasca, 1988). In addition, all versions of FLAC used by the Westinghouse Waste Isolation Division have been verified against the WIPP Second Benchmark Problem (Krieg, 1984).

3.5.2 Model Descriptions

Three baseline grids were used for the nine cases that were run for this analysis. These grids were first run without backfill or waste emplaced in the rooms. Two of the base grids were rerun with several different backfill configurations. Material properties common to all models are given in Tables 3-8, 3-9, and 3-10. The baseline grids are described below.

3.5.2.1 Half-Panel Room Interaction Model (BF1)

The first model, designated BF1, attempted to determine the effect of backfill on the stability of nearby excavations. A seven-room panel was modeled (3-1/2 rooms by symmetry). Figures 3-23 and 3-24 show two views of the grid for model BF1. Figure 3-25 shows the boundary conditions with the upper boundary about 100 m (330 ft) above the excavations and the lower boundary about 50 m (165 ft) below the excavations. The right boundary was 100 m (330 ft) from the right-most excavation. Excavations were all 4 m (13 ft) high by 10 m (33 ft) wide, with 30.5-m (100-ft) wide pillars.

This model assumed the stratigraphy above the WIPP to be all halite, with the exception of clay seams. Clay seams above and below the excavation were modeled using FLAC interfaces. Material properties for the halite and the clay seams are included in Tables 3-8, 3-9, and 3-10.

The base model (no backfill) was run for 227 model years. The rooms were excavated simultaneously and instantaneously. Four additional backfilled cases were run. In the first backfill case, only the center (left-most) room was excavated, and the model was run for 50 model years. This case represents the best situation for backfill improving stability. By not excavating the other rooms, the first case simulated emplacing 100 percent consolidated backfill instantaneously. In the second case, crushed salt backfill was emplaced in all but the center room immediately after excavation. In the third case, an air gap was simulated above the crushed salt backfill. In the final case, waste drums were included in the crushed salt backfill. All cases were run for at least 50 model years, except the waste drum model, which could only be run to 22 model years due to model execution problems. All backfill materials, including the waste drums and the air gap, were modeled using FLAC's double-yield constitutive model. Description of the constitutive model and derivation of the backfill parameters are discussed in Section 3.5.3.

3.5.2.2 Single-Room Maximum Subsidence Model (BF2)

The second base model, designated BF2, attempted to determine the maximum subsidence-induced vertical displacement. A single disposal room and a pillar were modeled as extending to the surface. These models simulated a horizontally infinite panel, with a

25 percent extraction ratio. Figures 3-26 through 3-28 show views of the grid for model BF2. Figure 3-29 shows the boundary conditions. The upper boundary of the model was the ground surface, 644 m (2,115 ft) above the excavation. The lower boundary was 74 m (243 ft) below the excavation. The single room was 10 m (33 ft) wide and 4 m (13 ft) high. The pillar was 30.5 m (100 ft) wide.

Figure 3-29 shows the stratigraphy used for model BF2, which used the WIPP Reference Stratigraphy (Krieg, 1984) from the bottom of the model to 100 m (330 ft) above the room. The stratigraphy was modeled as all salt from 100 m (330 ft) above the room up to the Rustler Formation, 390 m (1,280 ft) above the excavation. The stratigraphy from the Rustler Formation to the surface is modeled as a soft sandstone. Tables 3-8, 3-9, and 3-10 list the properties for materials used in the model.

The base model (no backfill) was run for 240 model years. The room was excavated instantaneously. Five additional backfilled cases were run. Crushed salt, crushed salt with air gap, and crushed salt with waste drum cases similar to the half panel model cases were run. The backfill was emplaced in the model immediately after excavation. This avoided computing difficulties resulting from the deformed geometry of the rooms. In addition, the crushed salt parameters were altered to produce backfill 25 percent stiffer and 25 percent softer than the baseline backfill. These backfill parameters are described in Section 3.5.3. No 100 percent preconsolidated backfill case was run, because the model was a single room. The backfill models were run at least 30 model years beyond backfill emplacement, except for the waste drum model, which could only be run to 17 model years because of excessive backfill deformations.

3.5.2.3 Full-Panel Subsidence Model (BF3)

Model BF3, a larger model of two disposal panels and four access drifts (half by symmetry), attempted to determine the curvature of the subsidence trough. Figures 3-30 and 3-31 show different views of the grid. Figure 3-32 shows boundary conditions for the model. The upper boundary of the model simulated the ground surface and was 644 m (2,115 ft) above the excavations. The lower boundary was 203 m (666 ft) below the excavations. The right boundary was about 740 m (2,428 ft) away from the right-most excavation. Boundary locations were selected so as to capture the shape of the subsidence trough.

The stratigraphy for model BF3 is shown in Figure 3-32. Material properties are given in Tables 3-8, 3-9, and 3-10. The stratigraphy was assumed to be all halite up to the Rustler Formation. The Rustler Formation (except for the unnamed lower member) was modeled as a Mohr-Coulomb material, with anhydrite material parameters. The material above the Rustler Formation and the unnamed lower member of the Rustler were modeled as Mohr-Coulomb material, with generic soft sandstone material parameters (listed as "Non-Halite Overburden" in Table 3-9).

3.5.3 Backfill Constitutive Model and Material Parameters

Backfill was modeled in FLAC using the built-in double-yield constitutive model. This was intended to represent a material in which there may be significant irreversible compaction. The FLAC double-yield model is much simpler than the models used in SNL/NM codes (Butcher and Mendenhall, 1993). It is a plasticity model with a piece-wise linear stress-strain relationship. The major difference between FLAC and SNL/NM implementations is that in FLAC backfill compaction is not time-dependent, although the time-dependent closure of the excavations containing the backfill compensates for this in part. It is believed that, for the purposes of this report, the behavior of the backfill in FLAC adequately simulates real backfill behavior. The time-dependency and the internal mechanisms of backfill compression are not nearly as important as the end result.

Material parameters used for the FLAC backfill were taken from SNL/NM laboratory compaction tests (Holcomb and Hannum, 1982). The material properties for the backfill are given in Tables 3-11 and 3-12. Figure 3-33 shows the consolidation curve used for the crushed salt backfill. The curves used for the dense, loose, and air-gap backfill were derived from the Holcomb and Hannum curve. The dense backfill was derived by taking 75 percent of the strain used in the Holcomb and Hannum curve for the same pressure. The loose backfill was derived by taking 125 percent of the strain used in the Holcomb and Hannum curve for the same pressure. The air gap was modeled by adding 0.135 to the initial strain in the standard Holcomb and Hannum model. The 0.135 is the height of the air-gap (0.45 m [1.5 ft]) divided by the deformed height of the room at ten model years (3.33 m [10.9 ft]).

Waste drums were also modeled using FLAC's double-yield constitutive model. The consolidation curve used for the drums (Figure 3-34) was taken from SNL/NM model reports (Butcher and Mendenhall, 1993). This curve is for an "average" waste drum and its contents.

3.5.4 FLAC Modeling Results

The results of the individual FLAC models are presented below. Analysis of results are presented in Section 3.6.

3.5.4.1 Full-Panel Model Results

The full-panel model was run to 380 model years. At that point, the maximum vertical subsidence was 0.48 m (1.6 ft). The subsidence rate was about 0.4 millimeter per year (0.16 in./yr). At 380 model years, the remaining volume of the excavations was about 12 percent of the original. An estimation of the final subsidence that would have been achieved was made by dividing the 380 model-year subsidence results by 0.88, giving a final maximum vertical subsidence value of 0.55 m (1.8 ft). Table 3-13 summarizes the results of the model. Results are shown for the conditions at the ground surface, at the Culebra Dolomite level, and at a position 335 m (1,100 ft) from the edge of the panel, which is the distance of the waste shaft from the waste emplacement area. The 50-model-year and the estimated final values are given for all locations.

Figures 3-35 and 3-36 show the shape of the surface and the Culebra-level subsidence trough at various times. Figure 3-37 shows the variation in shape of the subsidence trough with depth. Figures 3-38 and 3-39 show the horizontal strain at the surface and the center of the Culebra Dolomite.

The horizontal strain at the Culebra Dolomite level, as shown in Figure 3-39, is less than the strain at the surface (Figure 3-38) and is opposite in sign. The horizontal strain at the surface near the center of the subsidence trough is negative, indicating compression, while the strain on the edges of the trough is positive, indicating tension. This strain profile is typical for horizontal strains across a subsidence trough at the surface. The opposite-sign strains at the Culebra Dolomite level are likely due to the relative position of the Culebra in the stratigraphic sequence. The rock units above the Salado Formation were modeled as stiff beds and deform together as a flexing beam. The Culebra Dolomite is located near the bottom of this beam and, therefore, exhibits strains which are opposite to the strains in the levels above the center-line (i.e., at the surface).

The displacements at a shaft were also analyzed. Although a three-dimensional model is required to give exact results, an estimation of the subsidence-induced displacements at the waste shaft can be determined by examining a point in the model located 335 m (1,100 ft) from the end of the panel. This is the diameter of the waste shaft pillar. Figures 3-40 and 3-41 show vertical and horizontal displacements on a vertical section 335 m (1,100 ft) from the shaft.

3.5.4.2 Single-Room Model Results

The results for the single-room FLAC model runs are presented in the Figures 3-42 to 3-44. Figure 3-42 shows the vertical subsidence at the surface for each of the backfill types. Figures 3-43 and 3-44, respectively, show the vertical and horizontal convergence of the excavation. As expected, the effect of the different backfill materials on subsidence is proportional to the initial and final relative density of the backfill. Denser backfill allows less convergence than looser backfill. The model with the waste drums shows almost no effect on subsidence, because of the very low initial density of the waste drums. The difference between the crushed salt backfill materials is, in practical terms, minimal.

3.5.4.3 Half-Panel Model Results

The purpose of the half-panel models was to determine the effect of backfilling on neighboring, nonbackfilled drifts. Figure 3-45 compares vertical convergence in the unbackfilled room for each model. Comparison between the five cases is best done through examination of stress and strain plots. Figures 3-46 to 3-53 show shear strain and effective stress around the unbackfilled drift at 10 and 20 model years after excavation. These plots show that the backfill does not significantly affect conditions around the unbackfilled drift until 20 model years after excavation. (The backfill effect would probably take much longer under realistic operating schedules.) In the models, the drifts were excavated and backfilled instantaneously at model time zero. Realistically, there would be a lag of at least five to seven years between excavation and backfilling. The effect of backfill on stability is dependent on the properties of the backfill and on the rate of backfill compaction, which is in turn dependent on the convergence rate of the rooms. A seven-year-plus delay between excavation and backfilling would result in significantly longer backfill compaction times.

3.6 Comparison and Evaluation of Results

This section presents a comparison and evaluation of the results of the four subsidence prediction methods and a summary of the FLAC modeling and observational results pertaining to room interaction. The subsidence calculations are based on the assumption that full closure of the rooms does occur and that the closure of the rooms will be entirely transmitted to the surface. Due to the viscoplastic nature of rock salt, it is reasonable to assume complete closure with time. However, some overlying strata, such as the dolomite beds at the Culebra, may reduce the surface subsidence to some degree through bridging or bulking effects.

Each of the different methods used in the assessment were verified separately for use with the WIPP site stratigraphy. Mass conservation, influence function, and NCB methods were validated against two case histories of potash mines in the vicinity of WIPP. The mass conservation and influence function methods provided satisfactory results, overestimating the actual subsidence measured to within 17 percent. The NCB method yielded even more accurate predictions, with a difference of 7 percent between the predicted and the maximum measured subsidence in the potash mine under study.

Despite the fact that the different methods are based on very different principles, all of the prediction methods yielded comparable results (Table 3-14). The maximum subsidence was obtained for the case of empty panels at the waste storage area. The mass conservation yielded a maximum value for this case of 0.86 m (2.8 ft); the influence function value was 0.56 m (1.8 ft); the prediction of the NCB method was 0.73 m (2.4 ft), and the finite difference model (FLAC) yielded 0.55 m (1.8 ft) for the full-panel model and 0.95 m (3.1 ft) for the single-room model. However, a more realistic scenario would be to consider that the waste emplacement area will, as a minimum, be filled with waste. The values of maximum subsidence for the case of stored waste without backfill were also within a narrow range for the different methods employed. For the case of stored waste without backfill, this maximum was 0.62 m (2.0 ft) for the mass conservation method, 0.40 m (1.3 ft) for the influence-function method, and 0.53 m (1.7 ft) for the NCB method. The FLAC model results are not available due to instability problems for that particular case. Several other scenarios were also considered for the waste emplacement area, i.e., emplacement of loose backfill around the waste and emplacement of compacted backfill around the waste. Also, for the shaft pillar area and for the northern experimental area, the cases of stowing the openings with loose backfill and with compacted backfill were analyzed. Table 3-14 illustrates the results of these analyses and, as it can be observed, the reduction of subsidence when using crushed rock salt backfill is negligible. The high porosity of the waste, which logically occupies most of the volume in the rooms, was primarily responsible for the final subsidence. Also, the effect of time was not taken into consideration in these assessments.

The differences in expected subsidence associated with emplacing loose crushed-salt backfill rather than no backfill at all in any of the three areas of the WIPP underground diminishes as the time between excavation and backfilling increases. Because of the high porosity of the loose backfill and the time required for the backfill to consolidate after it is placed, loose backfill placed many years after excavation is essentially equivalent to placing no backfill at all. There becomes no geomechanical advantage to placing the loose backfill many years after excavation.

Studies of horizontal strain at the surface above the waste emplacement area and at the shaft were also performed. Predicted strains (0.053 to 0.074 percent) and tilt (0.0068 to 0.036 degrees) associated with the shaft are far below NCB guidelines for an acceptable amount of horizontal strain or tilt (see Table 3-15). No structural or operational problems are expected in the shaft. Expected horizontal strains at the surface above the WIPP site (Table 3-16) are tolerable for many sensitive structures, such as mine shafts, high continuous brick walls, reinforced concrete curtain walls, and a continuous simple steel frame as indicated by Table 3-15. Strains will be smooth above the Salado Formation, and since there are no discontinuities to concentrate strain, the impact on the hydrologic properties should be minimal.

Table 3-1
Data and Data Sources Used in Subsidence Predictions

Data Description	Data Value	Data Source
Limit angle	60 degrees from horizontal	Kratzsch, 1983;[a] Powers, 1993[b]
Depth of the WIPP underground	644 meters	IT Corporation, 1993[c]
Waste emplacement room dimensions	Height = 4 meters Width = 10 meters Length = 91.5 meters	SNL/NM, 1991[d]
Pillar width between waste rooms	30.5 meters	SNL/NM, 1991[d]
Lithostatic pressure at underground excavation depth	14.8 MPa	IT Corporation, 1991[e]
Porosity of loose crushed salt backfill	44%	Holcomb and Hannum, 1982[f]
Porosity of compacted crushed salt backfill	21%	Valdivia, 1994[g]
Compaction pressure vs. porosity relationship for CH-TRU waste drums	Initial porosity = 77% Final consolidated porosity = 19% Change in porosity = 58%	Butcher and Mendenhall, 1993[h]
Compaction pressure vs. porosity relationship for CH-TRU waste and crushed salt backfill composite	Initial porosity (loose fill) = 70% Initial porosity (compact fill) = 65% Final consolidated porosity = 13% Change in porosity (loose fill) = 57% Change in porosity (compact fill) = 52%	DOE, 1991b[i]
Material properties of halite and argillaceous halite	Elastic modulus = 31.0×10^9 Pa Poisson's ratio = 0.25 Bulk modulus = 20.7×10^9 Pa Shear modulus = 12.4×10^9 Pa Mass density = 2,300 kg/m^3	Westinghouse, 1988[j]
Material properties of polyhalite	Bulk modulus = 65.8×10^9 Pa Shear modulus = 20.3×10^9 Pa Mass density = 2300 kg/m^3 Friction angle = 47.5 degrees Cohesion = 17.2×10^6 Pa	IT Corporation, 1993[c]
Material properties of 10% polyhalite/90% halite	Bulk modulus = 22.1×10^9 Pa Shear modulus = 13.2×10^9 Pa Mass density = 2300 kg/m^3	IT Corporation, 1993[c]
Material properties of anhydrite	Bulk modulus = 83.4×10^9 Pa Shear modulus = 27.8×10^9 Pa Mass density = 2300 kg/m^3 Friction angle = 29 degrees Cohesion = 27×10^6 Pa	IT Corporation, 1993[c]
Material properties of clay seams	Friction angle = 5 degrees	IT Corporation, 1993[c]

Refer to footnotes at end of table.

Table 3-1 *(Continued)*
Data and Data Sources Used in Subsidence Predictions

Data Description	Data Value	Data Source
Material properties of overburden above salt	Bulk modulus = 15.6 x 10^9 Pa Shear modulus = 10.8 x 10^9 Pa Mass density = 2300 kg/m^3 Friction angle = 30 degrees Cohesion = 30 x 10^6 Pa	Itasca, 1988[k]
Extraction ratio of WIPP underground areas	Waste emplacement area = 0.22 Shaft pillar area = 0.077 Northern experimental area = 0.072	SNL/NM, 1991[d]

[a]Kratzsch, H., 1983, *Mining Subsidence Engineering*, Springer-Verlag, New York.

[b]Powers, D. W., 1993, "Background Report on Subsidence Studies for the Potash Mines and WIPP Site Area, Southeastern New Mexico," consultant's report for IT Corporation, Albuquerque, New Mexico.

[c]IT Corporation, 1993, "Modeling of Stratigraphic Horizon Changes for a WIPP Access Drift Using FLAC," IT Corporation, Albuquerque, New Mexico.

[d]Sandia National Laboratories/New Mexico (SNL/NM) WIPP Performance Assessment Division, 1991, "Preliminary Comparison with 40 CFR Part 191, Subpart B for the Waste Isolation Pilot Plant, December 1991," *SAND91-0893*, Vol 1: Methodology and Results, Sandia National Laboratories, Albuquerque, New Mexico.

[e]IT Corporation, 1991, "Backfill Plan," IT Corporation, Albuquerque, New Mexico.

[f]Holcomb, D. J., and D. W. Hannum, 1982, "Consolidation of Crushed Salt Backfill Under Conditions Appropriate to the WIPP Facility," *SAND82-0630*, Sandia National Laboratories, Albuquerque, New Mexico.

[g]Valdivia, M. A., 1994, "Placement Conditions and Detection of Moisture Movement for Crushed Rock Salt Backfill," Master's Thesis, Department of Civil Engineering, University of New Mexico, Albuquerque, New Mexico.

[h]Butcher, B. M., and F. T. Mendenhall, 1993, " A Summary of the Models Used for the Mechanical Response of Disposal Rooms in the Waste Isolation Pilot Plant with Regard to Compliance with 40 CFR 191, Subpart B," *SAND92-0427*, Sandia National Laboratories, Albuquerque, New Mexico.

[i]U.S. Department of Energy (DOE), 1991b, "Evaluation of the Effectiveness and Feasibility of the Waste Isolation Pilot Plant Engineered Alternatives: Final Report of the Engineered Alternatives Task Force," *DOE/WIPP 91-007*, Vol. I, Rev. 0, U.S. Department of Energy, Carlsbad, New Mexico.

[j]Westinghouse Electric Corporation (Westinghouse), 1988, "Geotechnical Field Data and Analysis Report," *DOE/WIPP 89-009*, Carlsbad, New Mexico, pp. 5–8.

[k]Itasca Consulting Group, Inc. (Itasca), 1988, "Thermal-Mechanical Benchmark Testing of FLAC," *NRC-02-85-002*, prepared for U.S. Nuclear Regulatory Commission Division of Waste Management, Minneapolis, Minnesota.

CH-TRU = Contact-handled transuranic

kg/m^3 = Kilograms per cubic meter

Pa = Pascals

MPa = Megapascals

Table 3-2
Excavated Areas, Volumes, and Extraction Ratios for the WIPP Underground

Underground Area	Area Excavated[a], A_{exc} (10^3 m^2)	Area Enclosed[b], A_{encl} (10^3 m^2)	Extraction Ratio, $a=A_{exc}/A_{encl}$	Volume Excavated V_{exc} (10^3 m^3)	Volume Enclosed V_{encl} (10^3 m^3)	Average Excavation Height M (m)
Waste emplacement area	111.52	506.8	0.22	436.0	2008.0	3.91
Shaft pillar area	21.84	283.6	0.077	78.07	1037.2	3.57
Northern experimental area	21.61	298.1	0.072	71.90	1090	3.33

[a]Area excavated is defined as the plan area of the underground that has been mined in that region. Areas reported are from Sandia National Laboratories/New Mexico WIPP Performance Assessment Division, 1991, "Preliminary Comparison with 40 CFR 191, Subpart B for the Waste Isolation Pilot Plant" (SNL/NM, 1991).

[b]Area enclosed is defined as the large plan area of the underground that includes the excavated area and the pillars between rooms and drifts. Areas reported are from SNL/NM, 1991.

Table 3-3
Maximum Subsidence With and Without Backfill Material Using Mass Conservation Calculation

Underground Area	Extraction Ratio a	Initial Average Excavation Height M (m)	Contents of Excavation	Porosity n	Maximum Subsidence S_{max} (m)
Waste emplacement area	0.22	3.91	Empty	1.00	0.86[a]
			Waste only	0.72[b]	0.62
			Waste plus loose backfill	0.64[b]	0.55
			Waste plus compacted backfill	0.61[b]	0.52
Shaft pillar area	0.077	3.57	Empty	1.0	0.28
			Loose backfill	0.44	0.12
			Compacted backfill	0.21	0.06
Northern experimental area	0.072	3.33	Empty	1.0	0.24
			Loose backfill	0.44	0.11
			Compacted backfill	0.21	0.05

[a]The maximum subsidence predicted here for the waste emplacement area does not include contact-handled transuranic waste drums. This estimate assumes completely empty rooms. This situation is not considered viable for the WIPP site.

[b]Value for porosity is an equivalent room porosity based on an assumed waste stack height of 2.68 m and a ventilation air gap above the waste/backfill of 0.71 m.

Table 3-4
Influence Factors for Potash Mine Profile B

X distance (ft)	2000	1750	1500	1250	1000	750	500	250	0
Influence Factor	0	0.017	0.16	0.5	0.836	0.976	1	1	1
X distance (ft)	-250	-500	-750	-1000	-1250	-1500	-1750	-2000	-2250
Influence Factor	1	1	1	1	0.978	0.888	0.710	0.370	0.128

ft = feet

Table 3-5
Maximum Expected Subsidence With and Without Backfill Using Influence Function Method

Underground Area	Contents of Excavation	Greatest Influence Factor in the Area	Maximum Expected Subsidence at Surface (m)
Waste emplacement area	Empty	0.65	0.56
	Waste only	0.65	0.40
	Waste plus loose backfill	0.65	0.36
	Waste plus compacted backfill	0.65	0.34
Shaft pillar area	Empty	0.36	0.10
	Loose backfill	0.36	0.04
	Compacted backfill	0.36	0.02
Northern experimental area	Empty	0.32	0.08
	Loose backfill	0.32	0.04
	Compacted backfill	0.32	0.02

Table 3-6
National Coal Board Method Maximum Subsidence Predictions for the WIPP Site

Backfill Scenario	Northern Experimental Area (m)	Shaft Pillar Area (m)	Waste Emplacement Area[a] (m)
Empty rooms—no backfill	0.02	0.04	0.53
Rooms backfilled with loose crushed salt	0.01	0.02	0.47
Rooms backfilled with compacted crushed salt	0.01	0.01	0.44

[a]Subsidence estimates for the waste emplacement area are based on the assumption that untreated contact-handled transuranic waste drums are placed in the waste rooms and access drifts.

Table 3-7
National Coal Board Method Maximum Horizontal Strain Predictions for the WIPP Site at the Surface

Backfill Scenario	Northern Experimental Area (%)	Shaft Pillar Area (%)	Waste Emplacement Area[a] (%)
Empty rooms—no backfill	0.0084	0.013	0.053
Rooms backfilled with loose crushed salt	0.0037	0.0058	0.047
Rooms backfilled with compacted crushed salt	0.0018	0.0028	0.045

[a]Subsidence estimates for the waste emplacement area are based on the assumption that untreated contact-handled transuranic waste drums are placed in the waste rooms and access drifts.

Table 3-8
FLAC[a] Model Time-Dependent Material Properties

Property	Halite	Argillaceous Halite	Halite, 10% Polyhalite
Bulk modulus (GPa)	20.7	20.7	22.1
Shear modulus (GPa)	12.4	12.4	13.2
Density (kg/m^3)	2,300	2,300	2,300
Activation energy (cal/mol)	12,000	12,000	12,000
A	4.56	4.56	4.56
B	127	127	127
D ($Pa^{-4.9}/s$)	5.79×10^{-36}	1.74×10^{-35}	5.21×10^{-36}
n	4.9	4.9	4.9
Gas constant (cal/mol K)	1.987	1.987	1.987
Critical strain rate	5.39×10^{-8}	5.39×10^{-8}	5.39×10^{-8}

[a]FLAC = Fast Lagrangian Analysis of Continua.
GPa = Gigapascal(s).
kg/m^3 = Kilogram(s) per cubic meter.
cal/mol = Calorie(s) per mole.
$Pa^{-4.9}/s$ = Pascal(s) to the negative 4.9 per second.
cal/mol K = Calorie(s) per mole kelvin.
A,B,n = unitless model factors.
D = model factor.

Table 3-9
FLAC[a] Elastic Material Properties

Property	Anhydrite	Polyhalite	Non-Halite Overburden
Bulk modulus (GPa)	83.4	65.8	15.6
Shear modulus (GPa)	27.8	20.3	10.8
Density (kg/m^3)	2,300	2,300	2,300
Cohesion (MPa)	27	17.2	30
Friction (deg)	29	46.5	30

[a]FLAC = Fast Lagrangian Analysis of Continua.
GPa = Gigapascal(s).
kg/m^3 = Kilogram(s) per cubic meter.
MPa = Megapascal(s).
deg = Degrees.

Table 3-10
FLAC[a] Clay Seam Material Properties

Property	Value
Normal stiffness (Pa/m)	1.0×10^{12}
Shear stiffness (Pa/m)	5.0×10^{10}
Cohesion	0.0
Friction (degrees)	5

[a]FLAC = Fast Lagrangian Analysis of Continua.
Pa/m = Pascal(s) per meter.

Table 3-11
Backfill Material Properties Used in FLAC[a] Model

Property	Value
Bulk modulus (GPa)	3.0
Shear modulus (GPa)	0.5
Density (kg/m^3)	2,300
Cohesion (Pa)	1×10^2
Tension Limit (Pa)	1×10^6

[a]FLAC = Fast Lagrangian Analysis of Continua.
GPa = Gigapascals.
kg/m^3 = kilograms per cubic meter.
Pa = Pascals.

Table 3-12
Stress-Strain Relationships for Crushed Salt Backfill Used in FLAC[a] Modeling

Crushed Salt		Crushed Salt with Air Gap		Dense Crushed Salt		Loose Crushed Salt		Waste Drums	
Plastic Volumetric Strain	Pressure (MPa)	Plastic Volumetric Strain	Pressure (MPa)	Plastic Volumetric Strain	Pressure (MPa)	Plastic Volumetric Strain	Pressure (MPa)	Plastic Volumetric Strain	Pressure (MPa)
0	0	0	0	0	0	0	0	0	0
0.05	1.1	0.03375	0.01	0.0375	1.1	0.0625	1.1	0.032	0.028
0.1	3.4	0.135	0.1	0.075	3.4	0.125	3.4	0.741	0.733
0.15	7.9	0.185	1.1	0.1125	7.9	0.1875	7.9	0.898	1.13
0.175	11.2	0.235	3.4	0.13125	11.2	0.21875	11.2	1.029	1.67
0.2	16.1	0.285	7.9	0.15	16.1	0.25	16.1	1.18	2.80
0.225	24.0	0.31	11.2	0.16875	24.0	0.28125	24.0	1.536	10.2
		0.335	16.1						
		0.36	24.0						

[a]FLAC = Fast Lagrangian Analysis of Continua.
MPa = Megapascal(s).

Table 3-13
Summary of FLAC[a] Full-Panel Model Results

Measurements at the Surface	Value	Distance from the Center of the Waste Emplacement Area
Maximum horizontal displacement (50 yr)	4.4 cm	501 m
Maximum horizontal displacement (final)	14.1 cm	577 m
Maximum vertical displacement (50 yr)	14.2 cm	0 m
Maximum vertical displacement (final)	54.9 cm	0 m
Maximum compressive horizontal strain (50 yr)	−0.013%	63 m
Maximum compressive horizontal strain (final)	−0.035%	42 m
Maximum tensile horizontal strain (50 yr)	0.011%	697 m
Maximum tensile horizontal strain (final)	0.053%	849 m
Maximum trough slope (50 yr)	0.014 deg	418 m
Maximum trough slope (final)	0.048 deg	523 m
Measurements at the Culebra Dolomite	**Value**	**Distance from the Center of the Waste Emplacement Area**
Maximum horizontal displacement (50 yr)	0.47 cm	686 m
Maximum horizontal displacement (final)	2.4 cm	501 m
Maximum vertical displacement (50 yr)	14.6 cm	0 m
Maximum vertical displacement (final)	55.7 cm	0 m
Maximum compressive horizontal strain (50 yr)	−0.0010%	0 m
Maximum compressive horizontal strain (final)	−0.007%	795 m
Maximum tensile horizontal strain (50 yr)	0.0018%	1099 m
Maximum tensile horizontal strain (final)	0.007%	240 m
Maximum trough slope (50 yr)	0.016 deg	407 m
Maximum trough slope (final)	0.051 deg	512 m
Measurements at the Shaft (335 m from Room 7)	**Value**	**Depth Below Surface**
Maximum horizontal displacement (50 yr)	2.9 cm	0 m
Maximum horizontal displacement (final)	11.7 cm	0 m
Maximum vertical displacement (50 yr)	2.7 cm	0 m
Maximum vertical displacement (final)	13.2 cm	0 m
Maximum vertical strain (50 yr)	−0.012%	0 m
Maximum vertical strain (final)	−0.034%	848 m
Vertical strain at Culebra Dolomite (50 yr)	−0.0010%	223 m
Vertical strain at Culebra Dolomite (final)	0.0034%	223 m
Maximum tilt (50 yr)	0.0068 deg	0 m
Maximum tilt (final)	0.036 deg	70 m

[a]FLAC = Fast Lagrangian Analysis of Continua.
cm = Centimeter(s).
deg = Degrees.
m = Meter(s).
yr = Year(s).

Table 3-14
Summary of Subsidence Prediction Results

Underground Area	Contents of Excavation	Subsidence				
		Mass Conservation (m)	Influence Function Method (m)	NCB Method (m)	FLAC Single Room Model (m)	FLAC Full Panel Model (m)
Waste emplacement area[a]	Empty	0.86	0.56	0.73	0.95	0.55
	Waste only	0.62	0.40	0.53	NA	NA
	Waste plus loose backfill	0.55	0.36	0.47	0.33	NA
	Waste plus compacted backfill	0.52	0.34	0.44	0.30	NA
Shaft pillar area	Empty	0.28	0.10	0.04	NA	0.13[b]
	Loose backfill	0.12	0.04	0.02	NA	NA
	Compacted backfill	0.06	0.02	0.01	NA	NA
Northern experimental area	Empty	0.24	0.08	0.02	NA	NA
	Loose backfill	0.11	0.04	0.01	NA	NA
	Compacted backfill	0.05	0.02	0.01	NA	NA

[a]Waste emplacement area includes Panels 1 through 8; Panels 2 through 8 are not yet excavated.

[b]At the Waste Shaft.

NCB = National Coal Board.
FLAC = Fast Lagrangian Analysis of Continua.
NA = Not available.

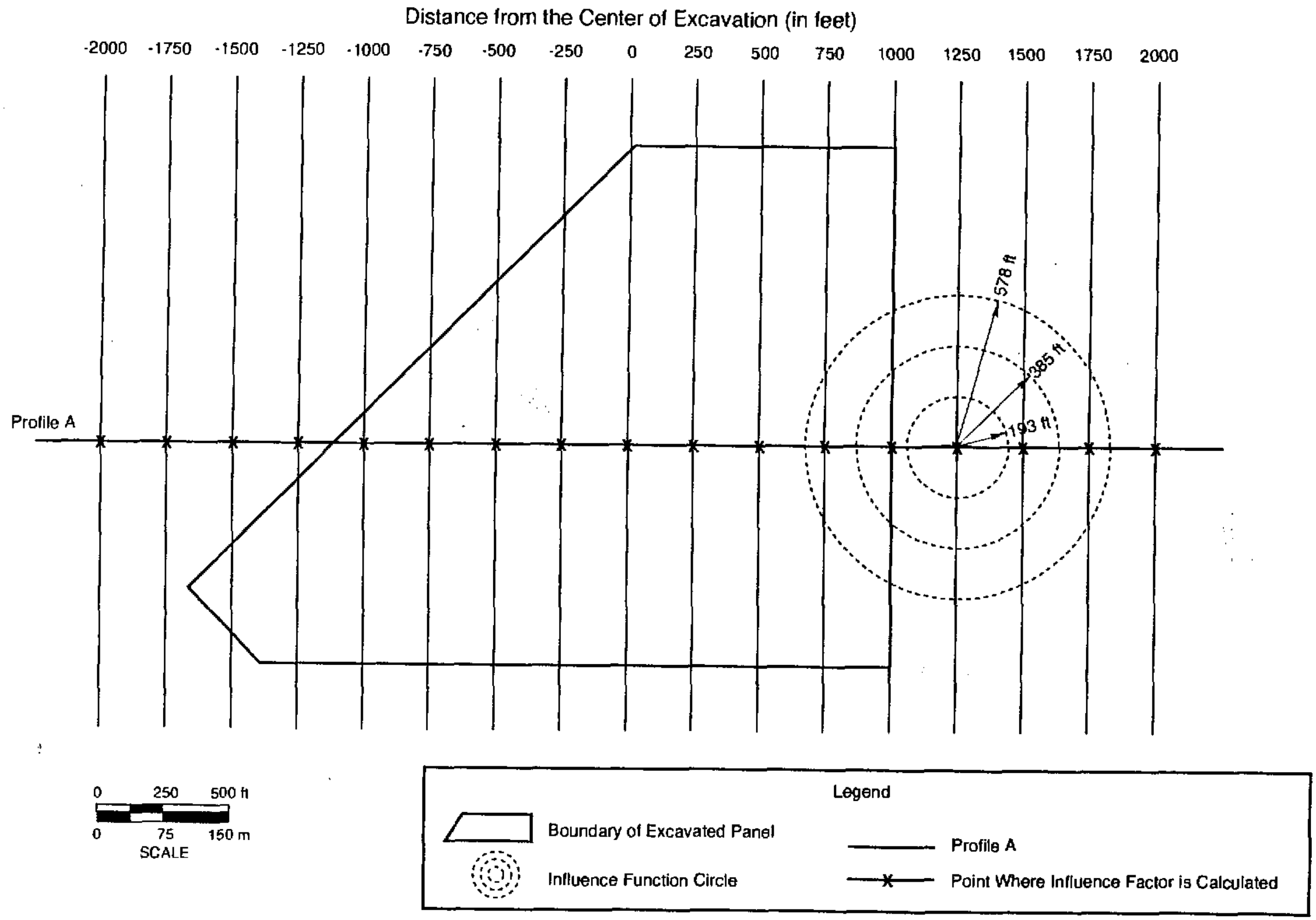

Figure 3-2

General Layout of Excavated Panel of Potash Mine Profile A

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6/7/94

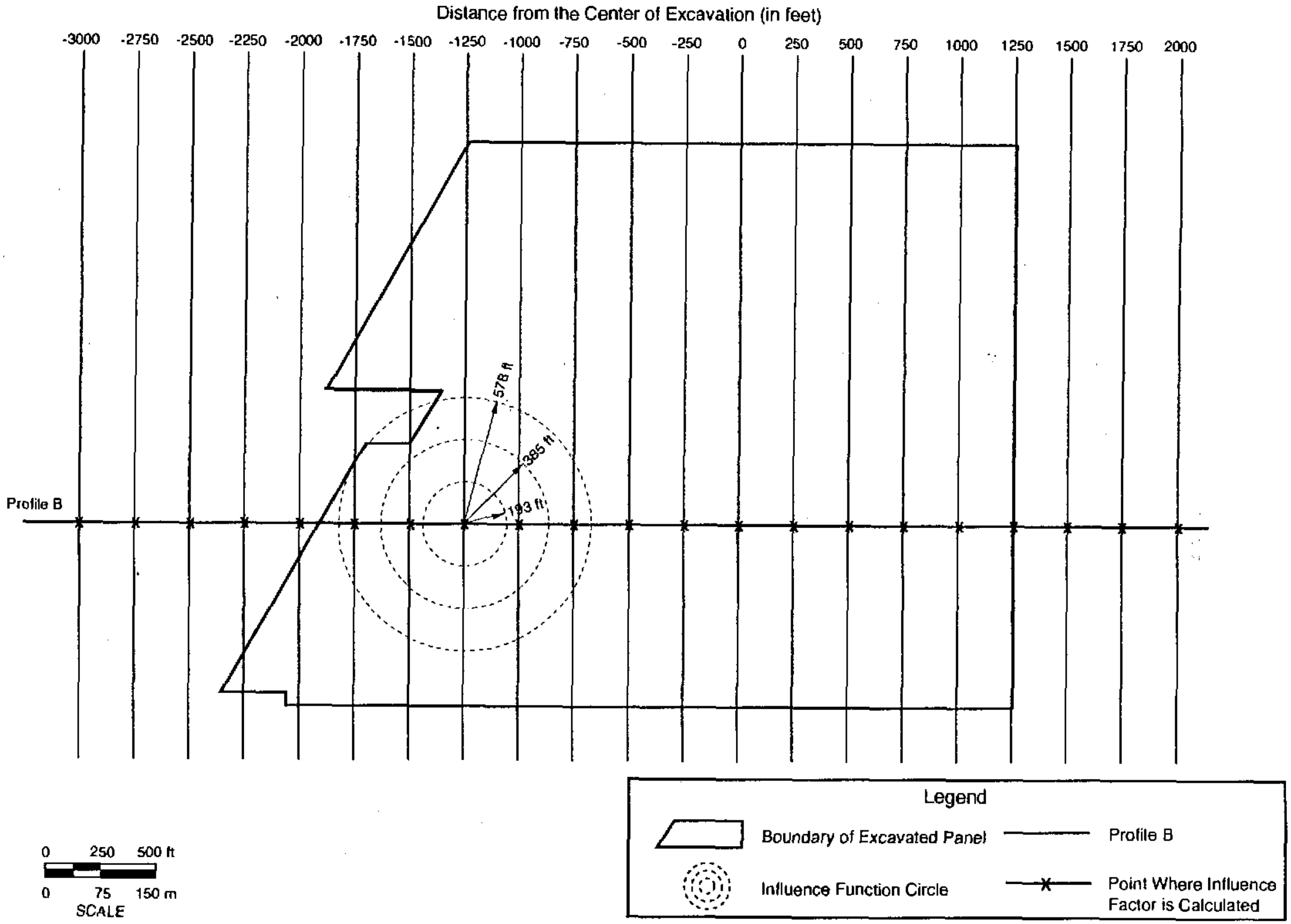

Figure 3-3
General Layout of Excavated Panel of Potash Mine Profile B

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Table 3-15
Maximum Horizontal Strain and Tilt Guidelines

Horizontal Strain (%)	Tilt Angle (minutes)	Comments
0.10	3.43	Tolerable strain for shafts[a]
0.05–0.10	NA	Tolerable for high continuous brick walls[b]
0.25–0.40	NA	Tolerable for reinforced-concrete building frame[b]
0.30	NA	Tolerable for reinforced-concrete curtain walls[b]
0.50	NA	Tolerable for steel frame, continuous simple steel frame[b]
NA	0.68	Tolerable for operation of a turbo generator[b]
NA	10.32	Tolerable for operation of railed cranes[b]
NA	34.37–68.75	Tolerable for floor drainage[b]

[a]Wagner, H., and M.D.G. Salamon, 1972, "Strata Control Techniques in Shafts and Large Excavations," Association Mine Managers South Africa, Papers and Discussion Vol. 1972–73, pp. 123–140.

[b]Voight, B., and W. Pariseau, 1970, "State of Predictive Art in Subsidence Engineering," *Journal Soil Mechanics and Foundation Division ASCE*, Vol. 96, SM2, pp. 721–749.

NA = Not available.

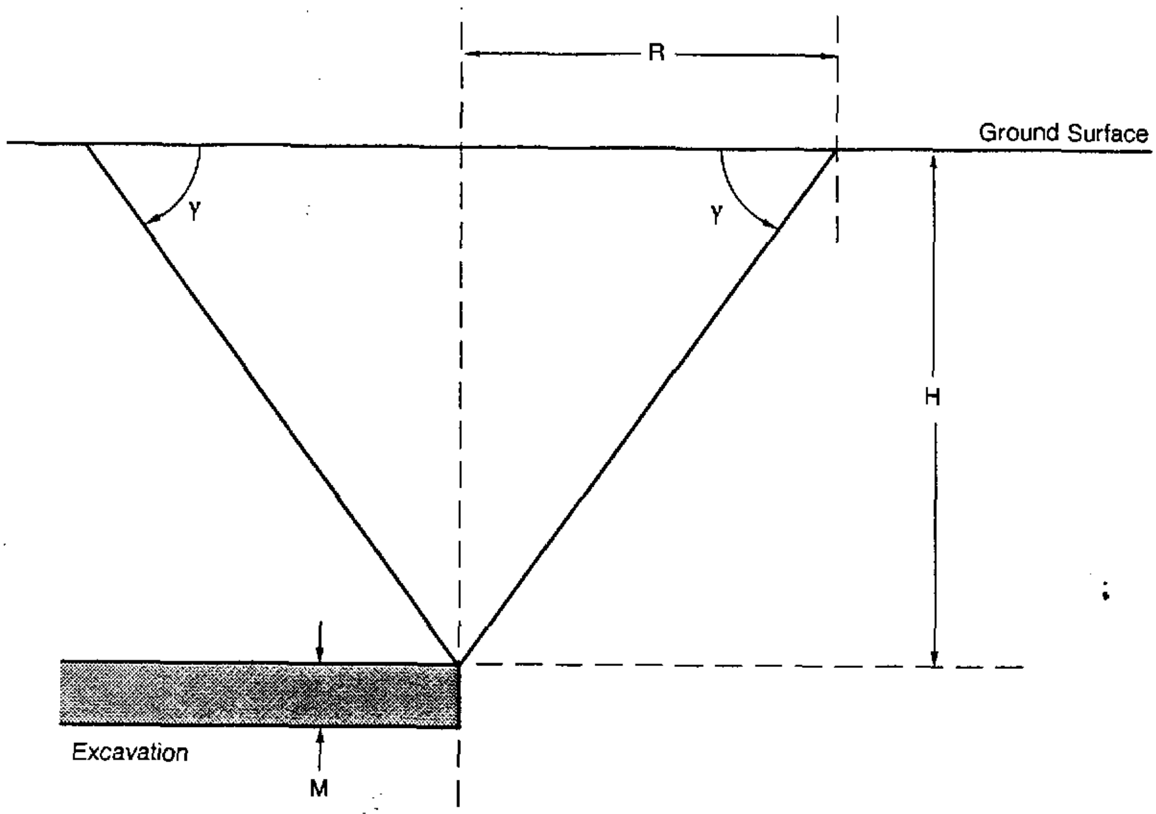
Table 3-16
Expected Horizontal Strains and Tilts Due To Subsidence

WIPP	FLAC[a] Full-Panel Model	NCB[b] Method
Maximum horizontal strain empty rooms with waste only	 0.053% NA	-- 0.074% 0.053%
Maximum shaft tilt 70 meters below the surface	2.16 minutes	NA
Maximum tilt of the shaft at the surface (50 years after excavation)	0.41 minutes	NA

[a]FLAC = Fast Lagrangian Analysis of Continua.

[b]NCB = National Coal Board.

NA = Not available.



LEGEND

R Radius of Influence

M Excavation Seam Height

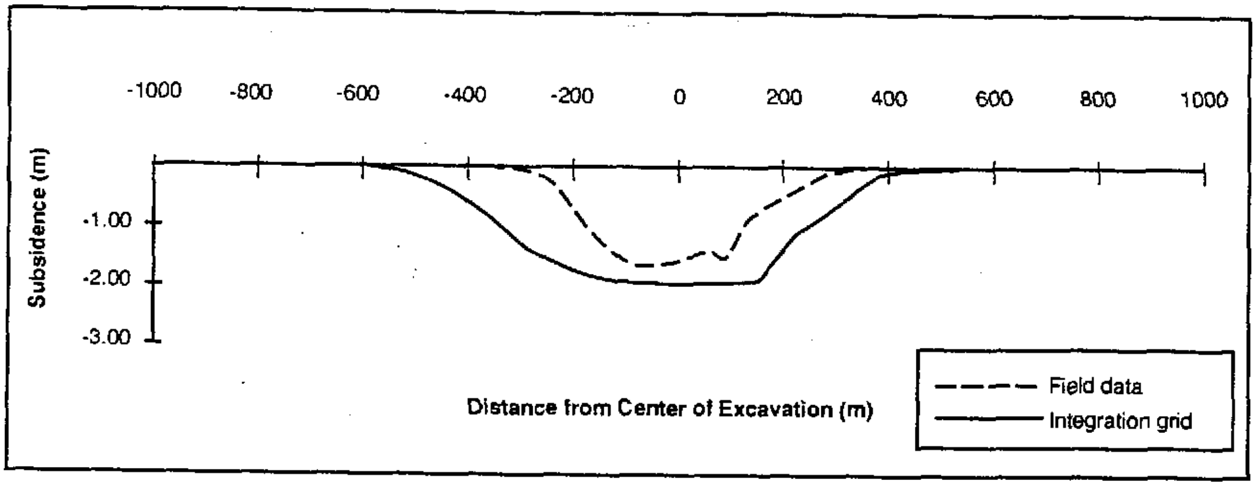
H Depth of Excavation

γ Limit Angle

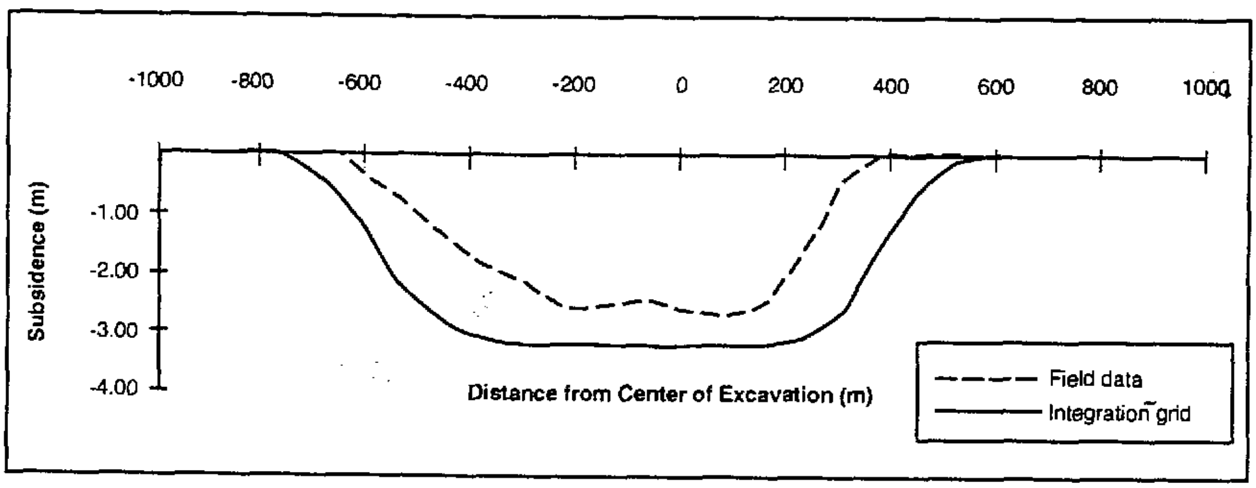
$R = H \cot(\gamma)$

Not to Scale

Figure 3-1
Schematic of How Radius of Influence is Determined – Influence Function Method



(a) Total Subsidence–Profile A



(b) Total Subsidence–Profile B

Figure 3-4
Comparison of Influence Function Method Results with Actual Field Measurements Across Potash Mine Profiles A and B

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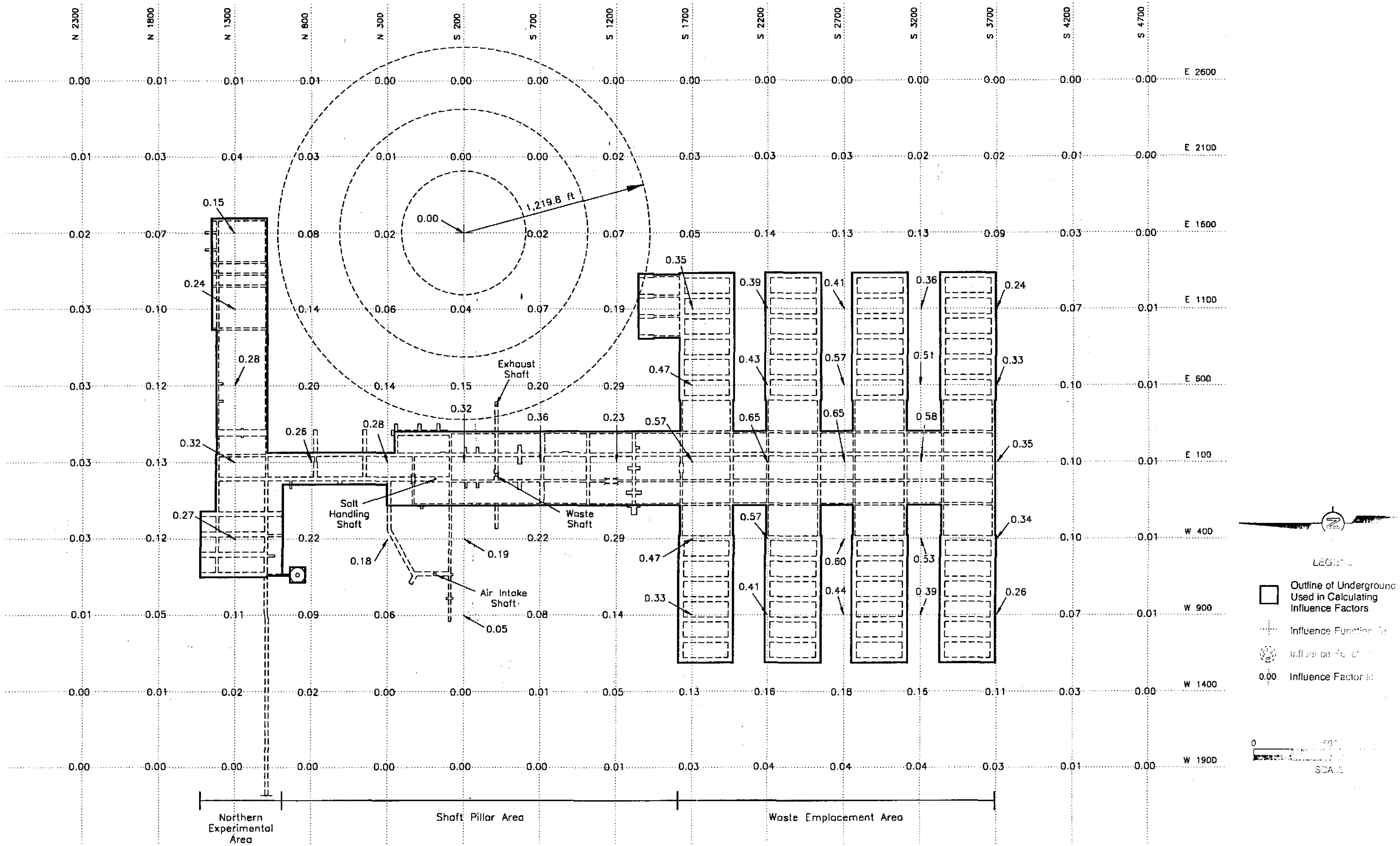
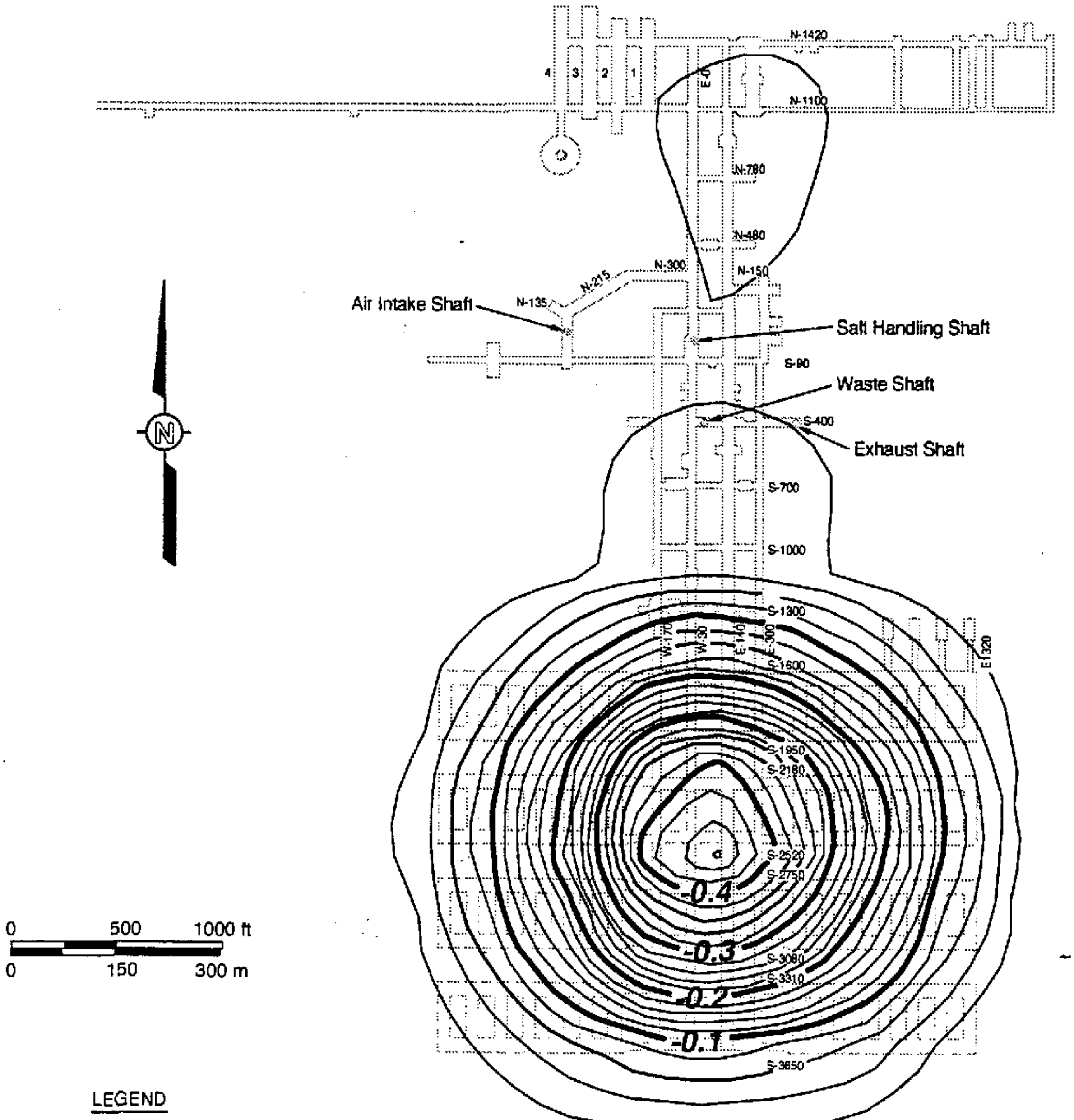


Figure
Layout of WIPP Undergr
and Influence Factors

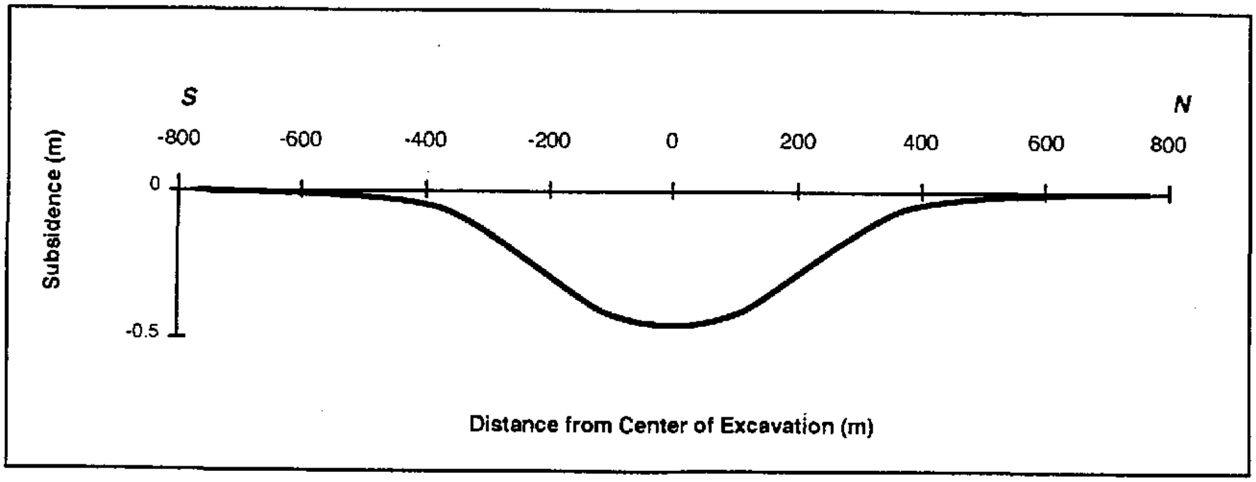


LEGEND

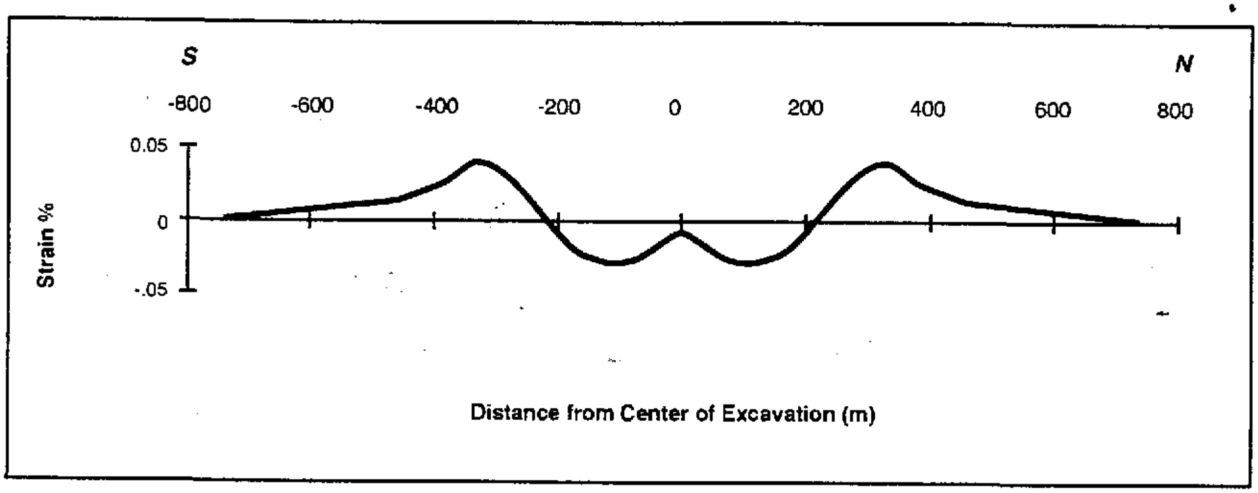
Contour Interval = 0.02 meters
Maximum Subsidence = 0.53 meters

Note:
Present surface topography in this area varies by more than 3 meters. Subsidence will not create a basin and should not be visible.

Figure 3-19
Contour Plot of Maximum Expected Surface Subsidence at the WIPP Site —National Coal Board (NCB) Method (Waste Only; No Backfill All Areas)

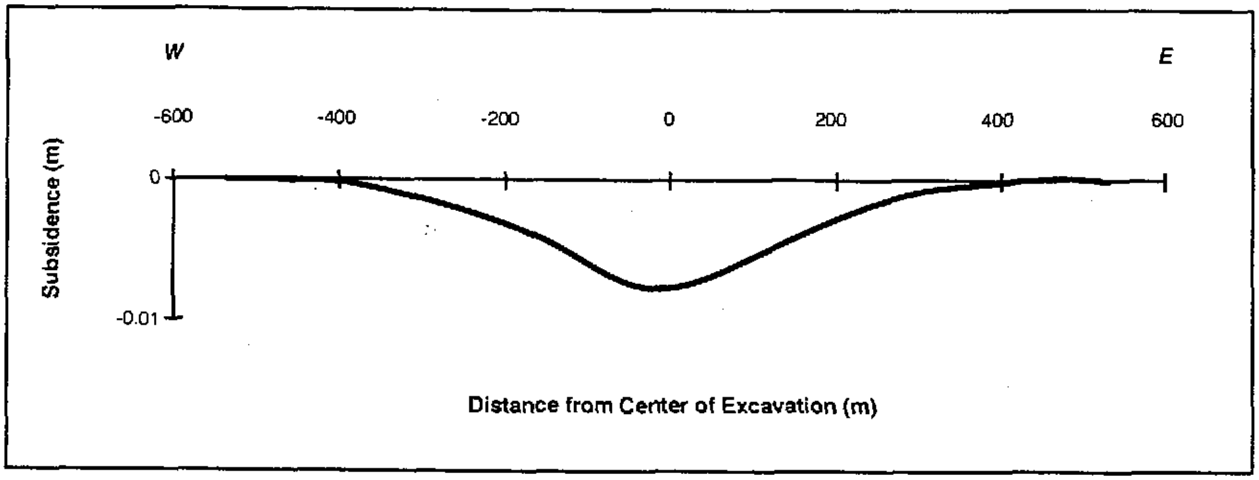


(a) Total Expected Subsidence

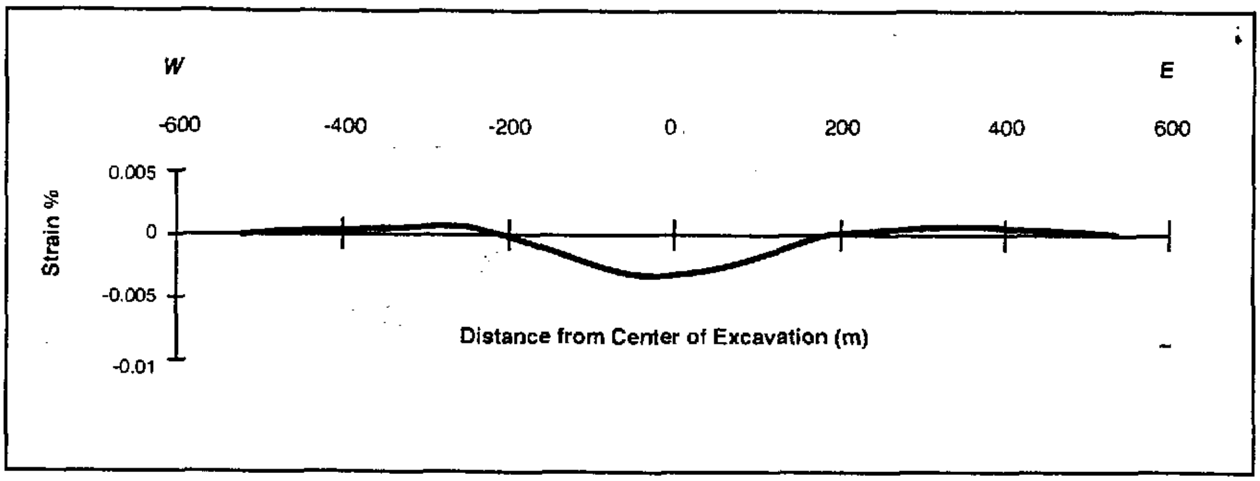


(b) Horizontal Strain

Figure 3-18
Expected Surface Subsidence and Horizontal Strain Across the Waste Emplacement Area Using the National Coal Board (NCB) Method (Compacted Backfill Around Waste)

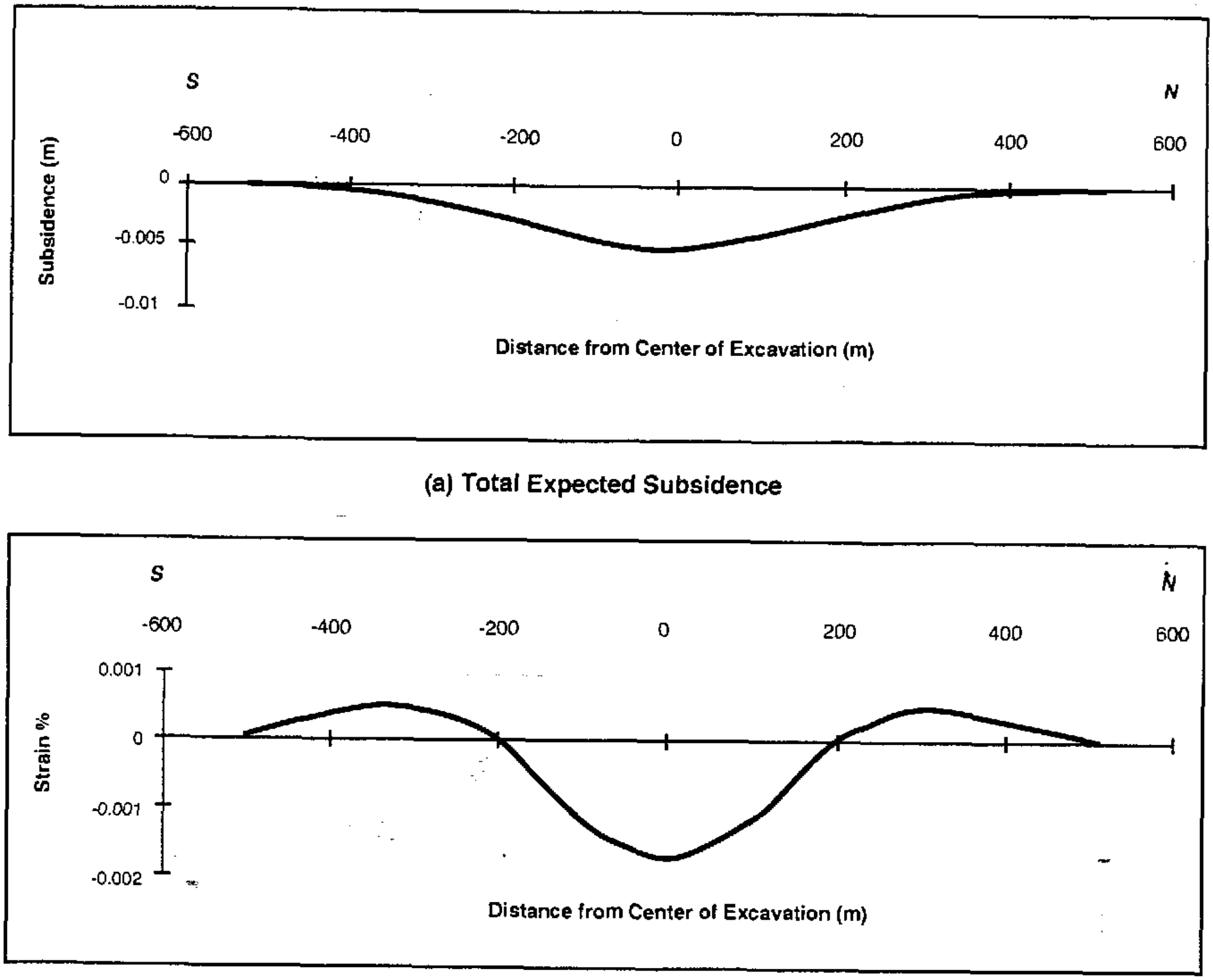


(a) Total Expected Subsidence



(b) Horizontal Strain

Figure 3-17
Expected Surface Subsidence and Horizontal Strain Across the Shaft Pillar Area Using the National Coal Board (NCB) Method (Compacted Backfill)



(a) Total Expected Subsidence

(b) Horizontal Strain

Figure 3-16
Expected Surface Subsidence and Horizontal Strain Across the Northern Experimental Area Using the National Coal Board (NCB) Method (Compacted Backfill)

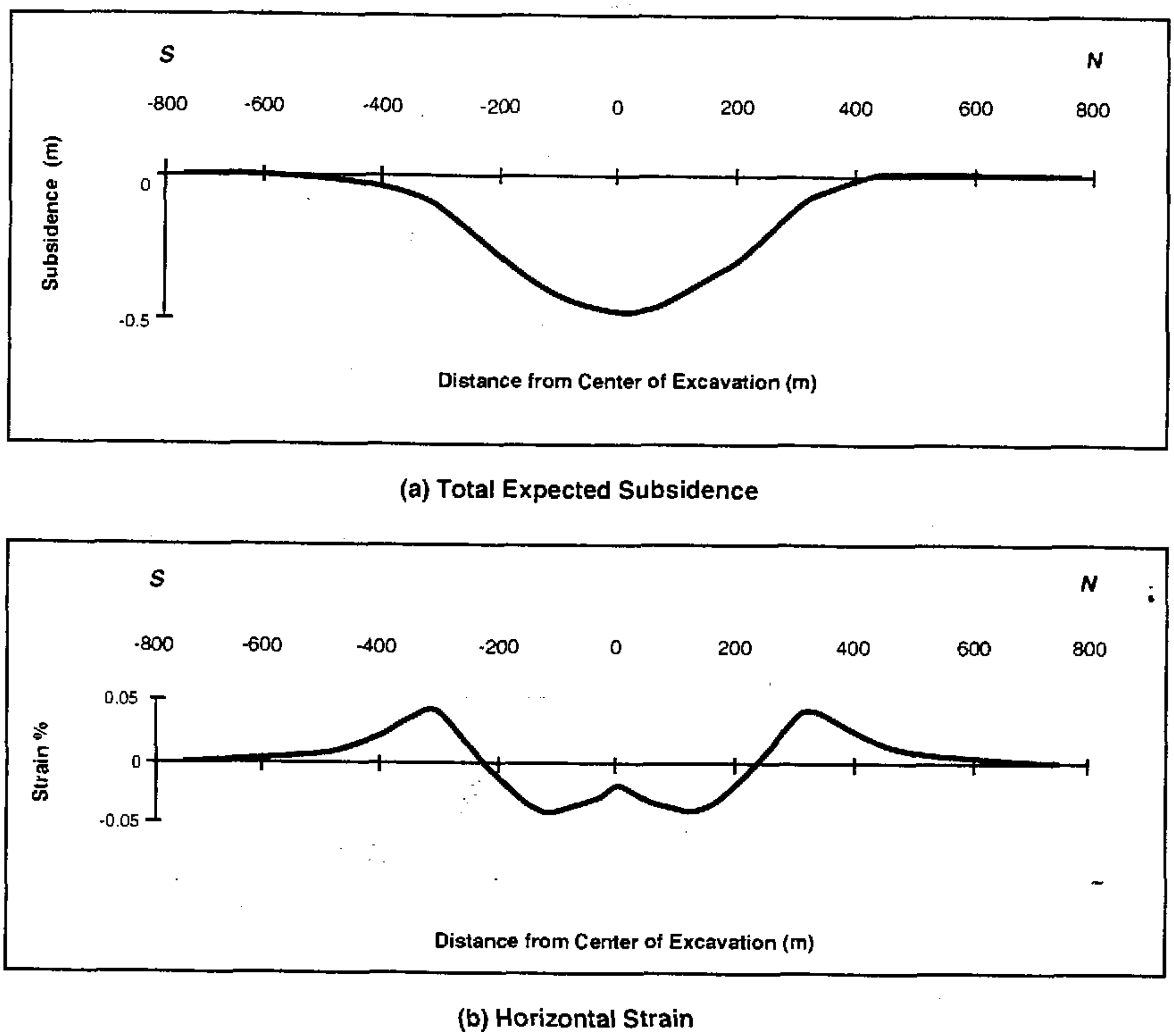
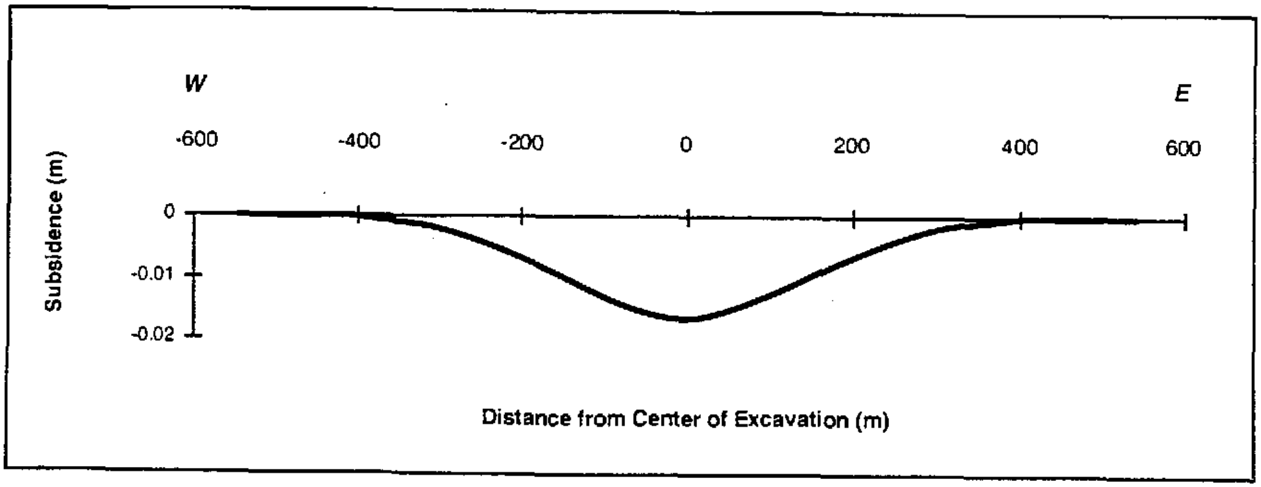
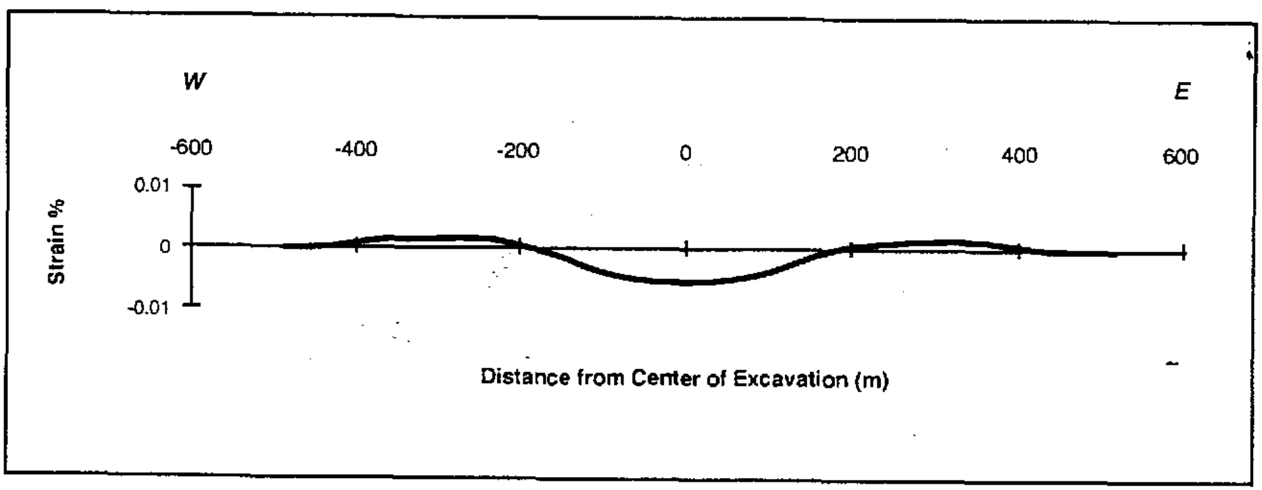


Figure 3-15
Expected Surface Subsidence and Horizontal Strain Across the Waste Emplacement Area Using the National Coal Board (NCB) Method (Loose Backfill Around Waste)

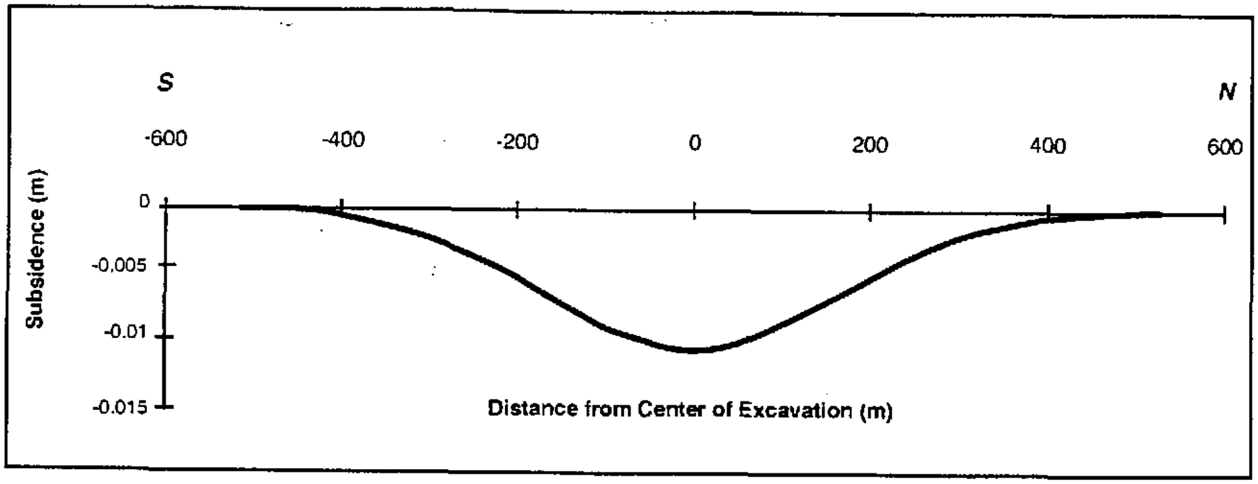


(a) Total Expected Subsidence

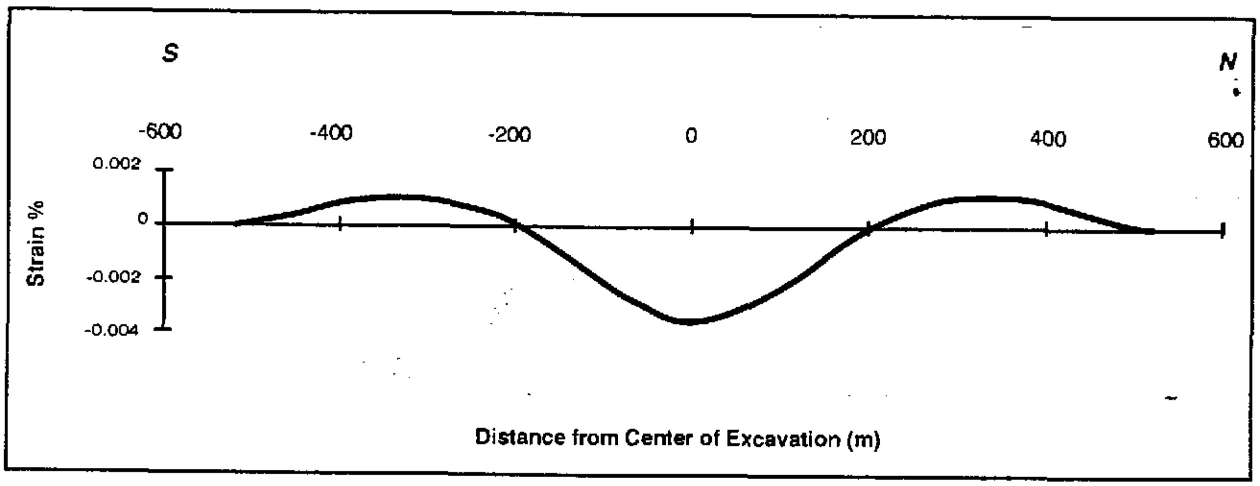


(b) Horizontal Strain

Figure 3-14
Expected Surface Subsidence and Horizontal Strain Across the Shaft Pillar Area Using the National Coal Board (NCB) Method
(Loose Backfill)

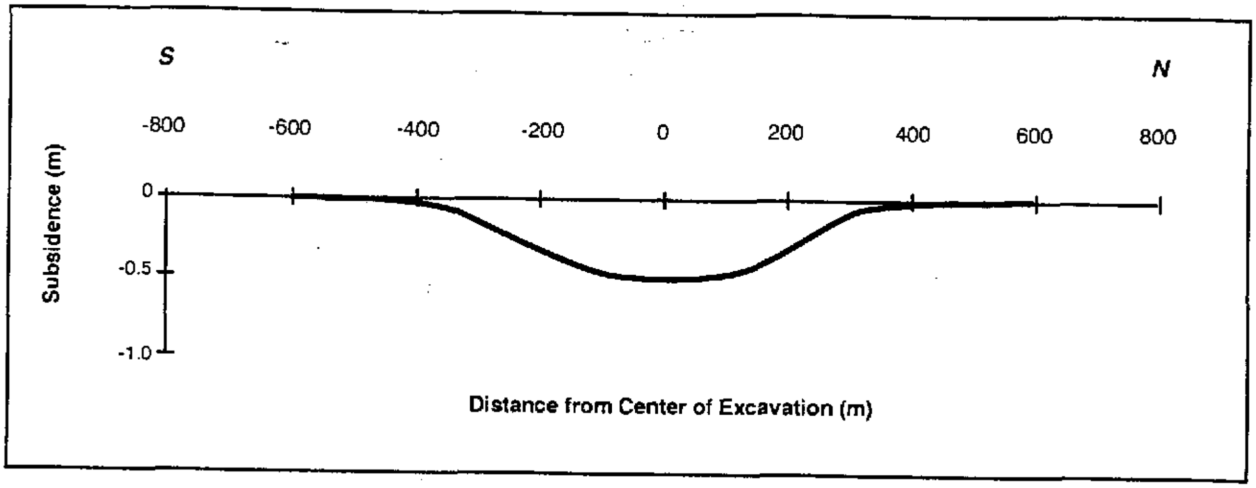


(a) Total Expected Subsidence

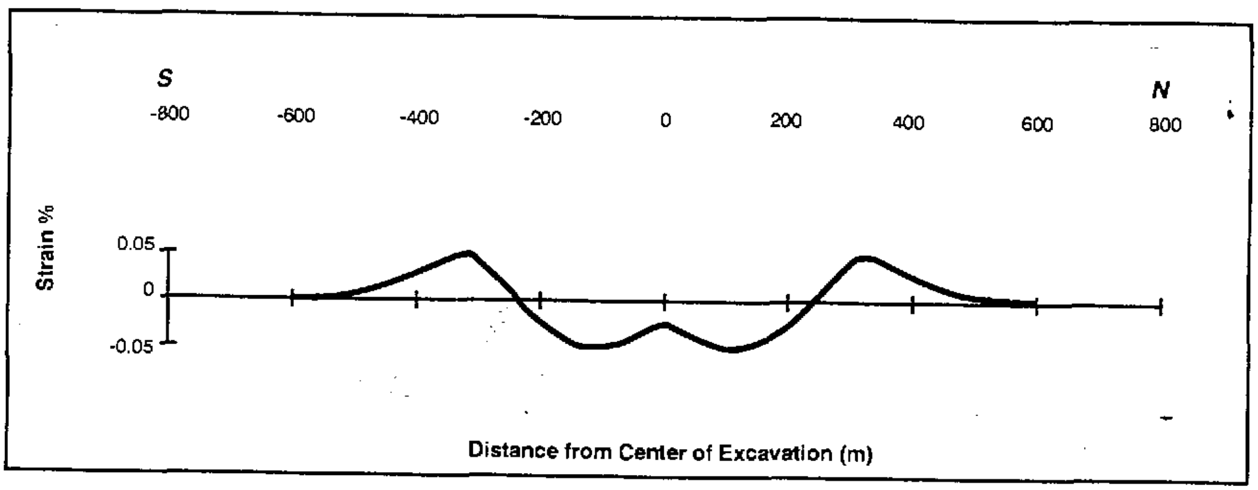


(b) Horizontal Strain

Figure 3-13
Expected Surface Subsidence and Horizontal Strain Across the Northern Experimental Area Using the National Coal Board (NCB) Method (Loose Backfill)

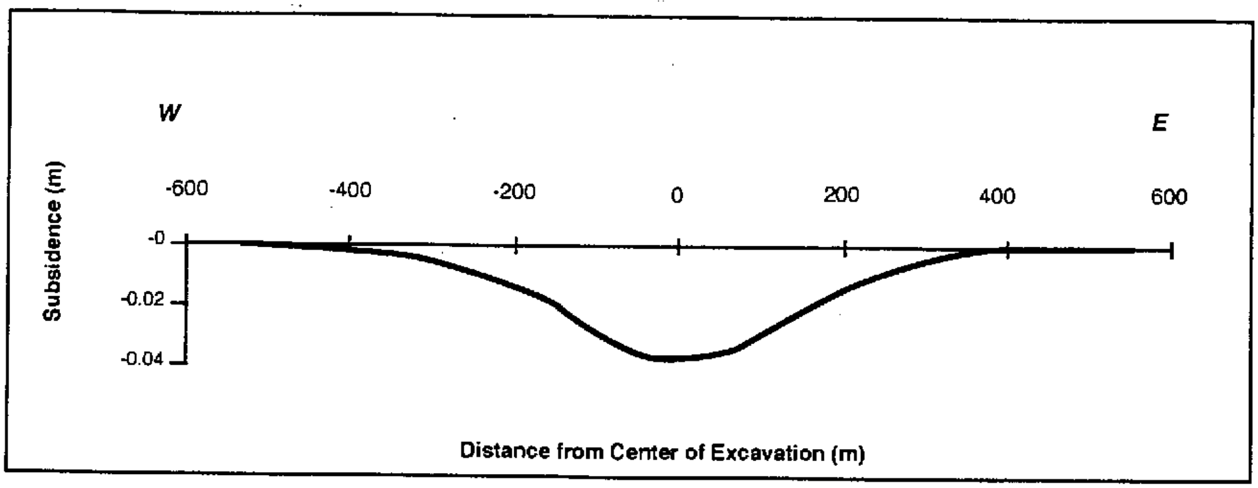


(a) Total Expected Subsidence

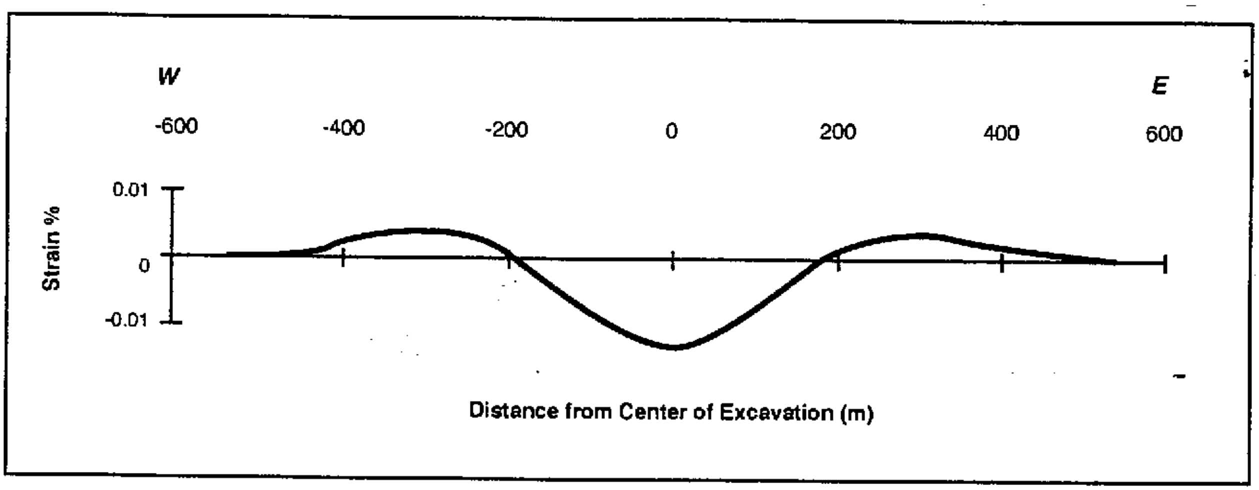


(b) Horizontal Strain

Figure 3-12
Expected Surface Subsidence and Horizontal Strain Across the Waste Emplacement Area Using the National Coal Board (NCB) Method (Waste Only–No Backfill)

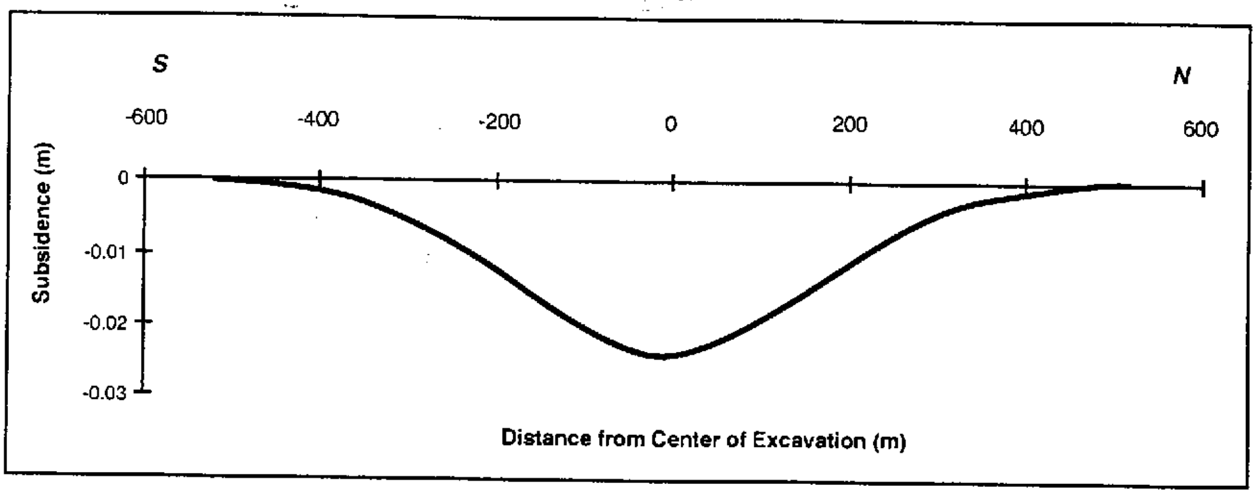


(a) Total Expected Subsidence

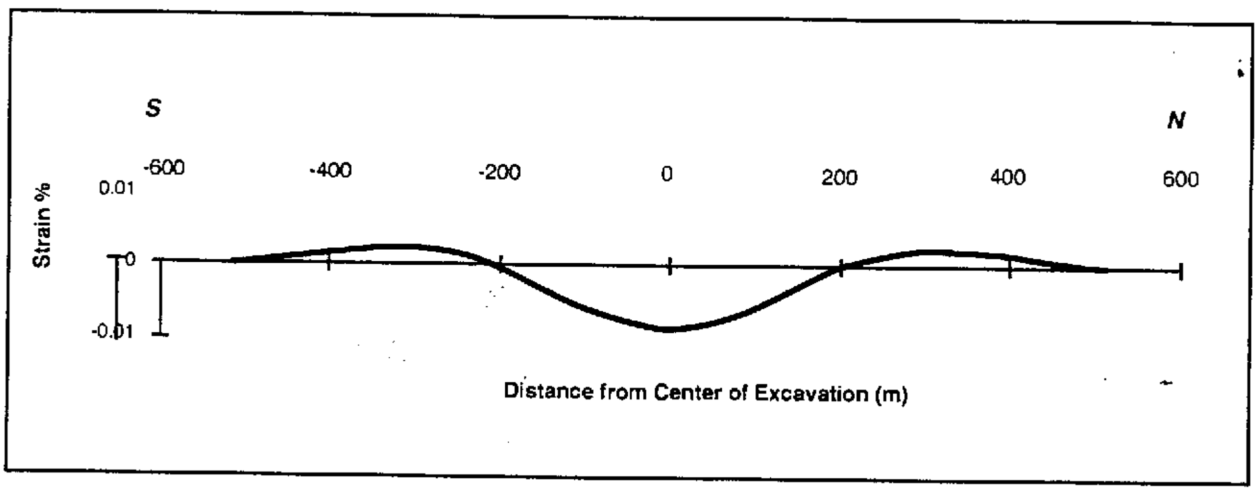


(b) Horizontal Strain

Figure 3-11
Expected Surface Subsidence and Horizontal Strain Across the Shaft Pillar Area Using the National Coal Board (NCB) Method (No Backfill)

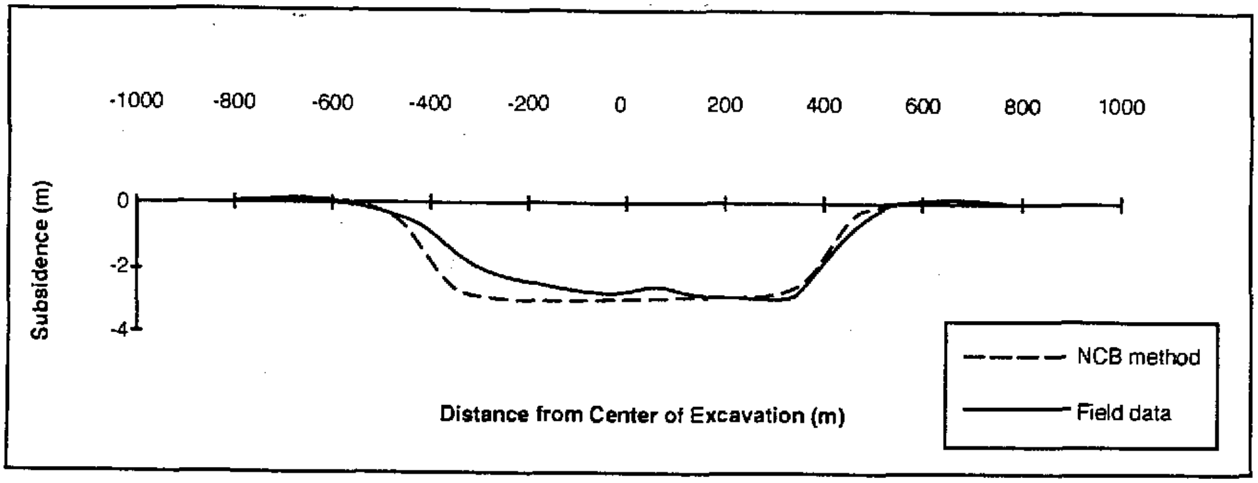


(a) Total Expected Subsidence

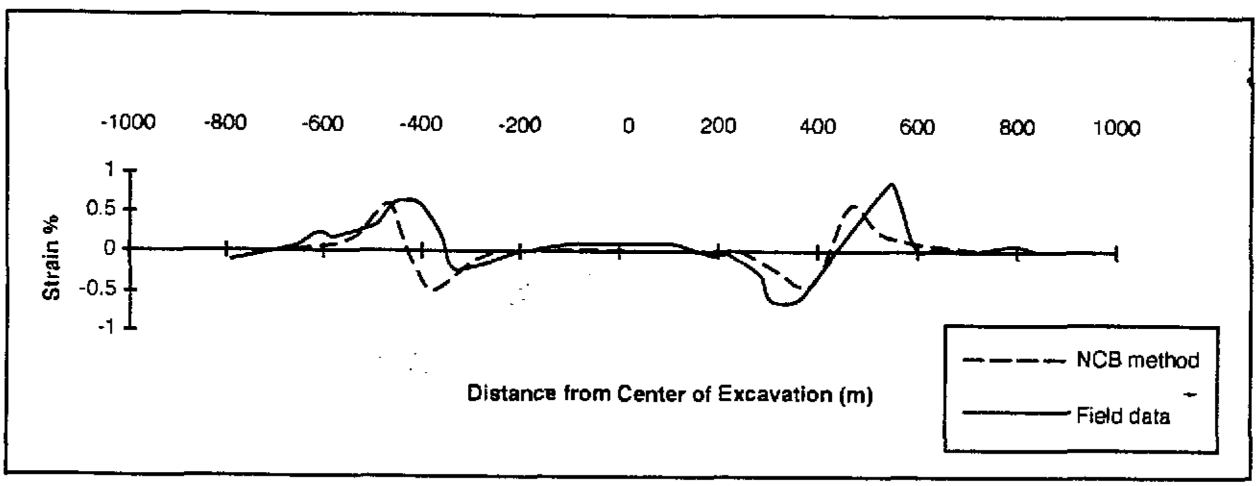


(b) Horizontal Strain

Figure 3-10
Expected Surface Subsidence and Horizontal Strain Across the Northern Experimental Area Using the National Coal Board (NCB) Method (No Backfill)

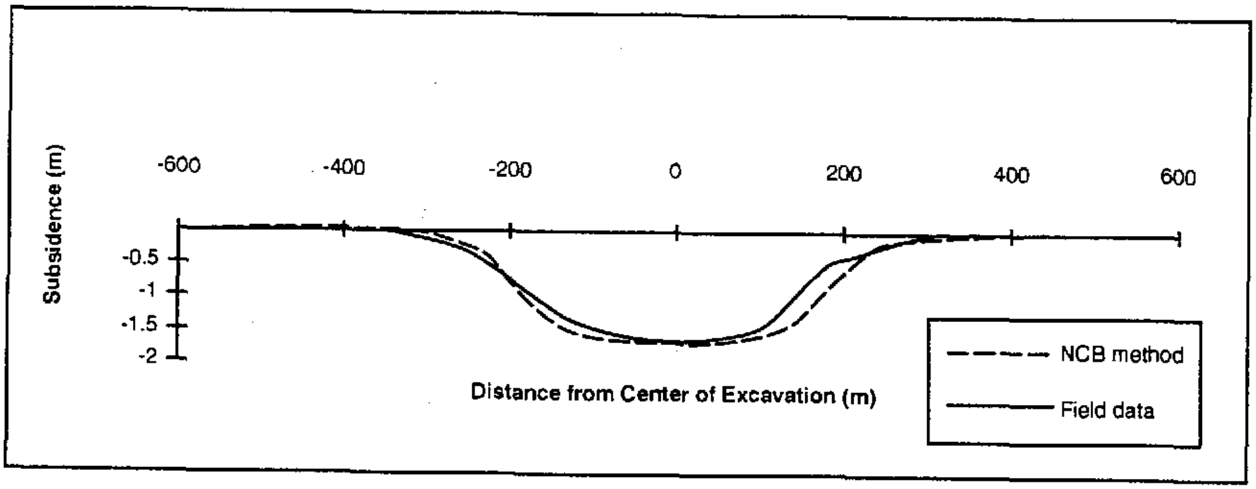


(a) Total Expected Subsidence

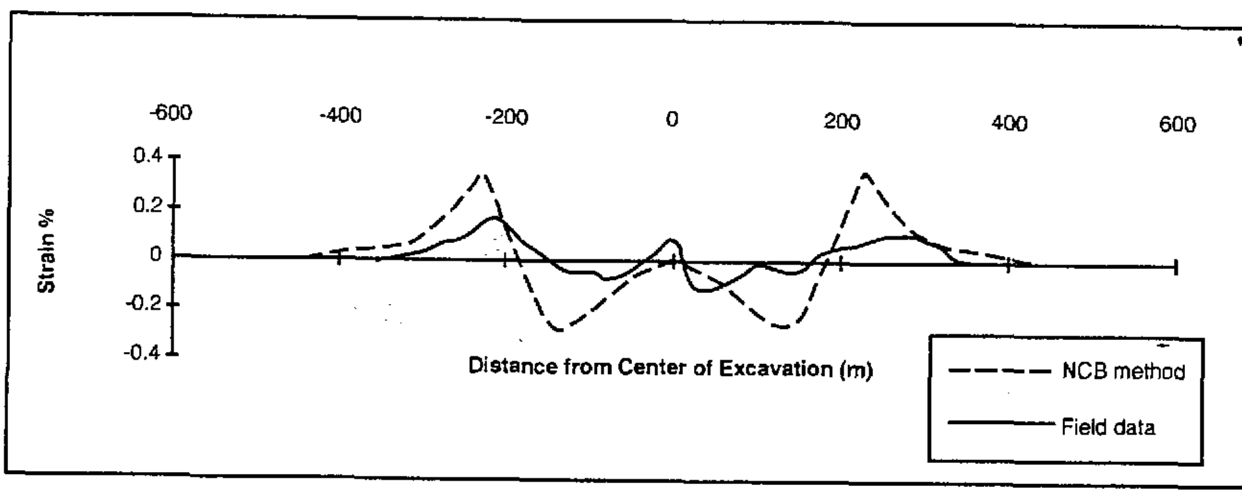


(b) Horizontal Strain

Figure 3-9
Comparison of Expected Surface Subsidence and Horizontal Strain with Actual Field Measurements Across Potash Mine Profile B--National Coal Board (NCB) Method



(a) Total Expected Subsidence



(b) Horizontal Strain

Figure 3-8
Comparison of Expected Surface Subsidence and Horizontal Strain with Actual Field Measurements Across Potash Mine Profile A–National Coal Board (NCB) Method

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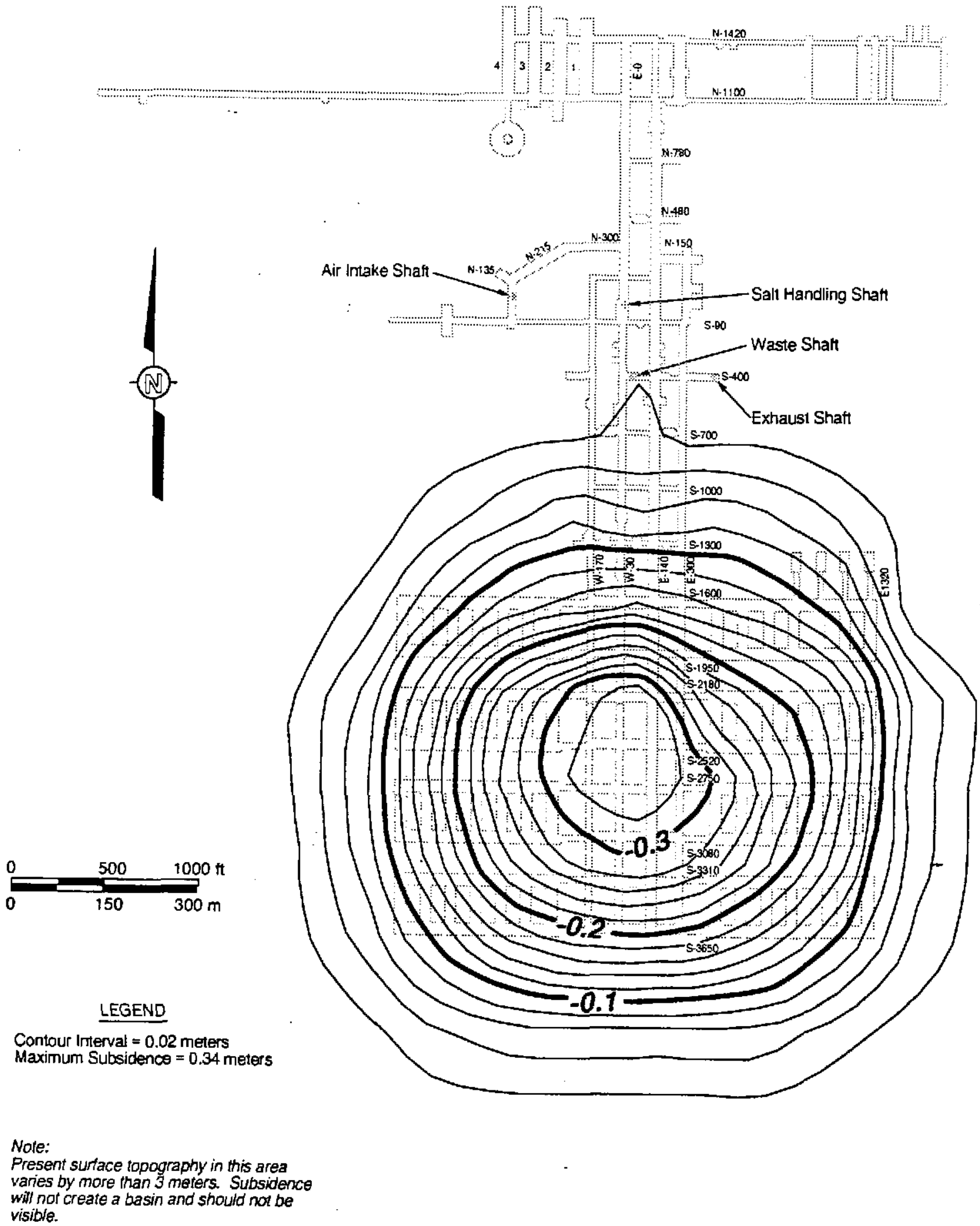

Figure 3-7
Contour Plot of Maximum Expected Surface Subsidence at the WIPP Site —Influence Function Method (Compacted Backfill)

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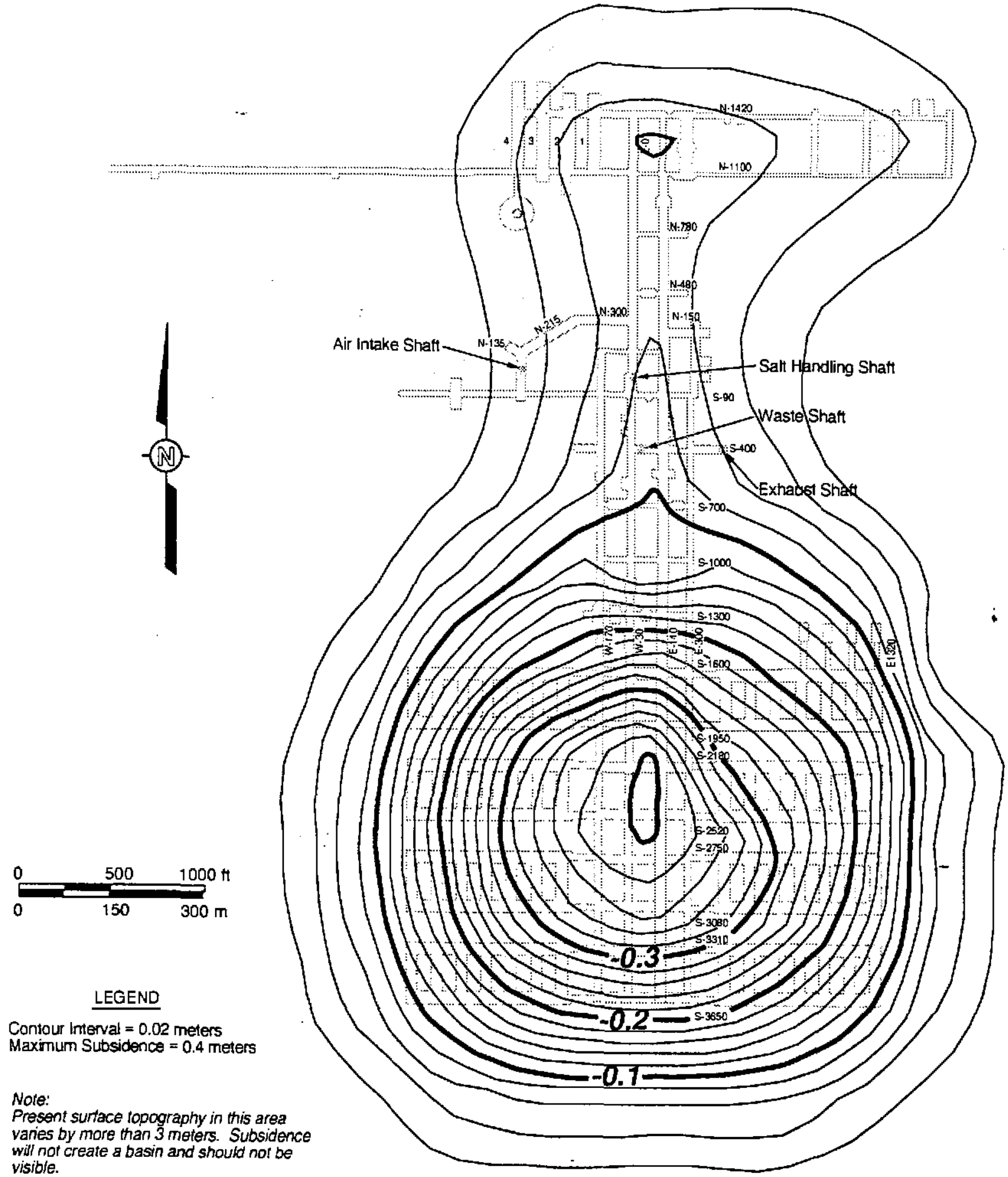

Figure 3-6
Contour Plot of Maximum Expected Surface Subsidence at the WIPP Site —Influence Function Method (Waste Only; No Backfill)

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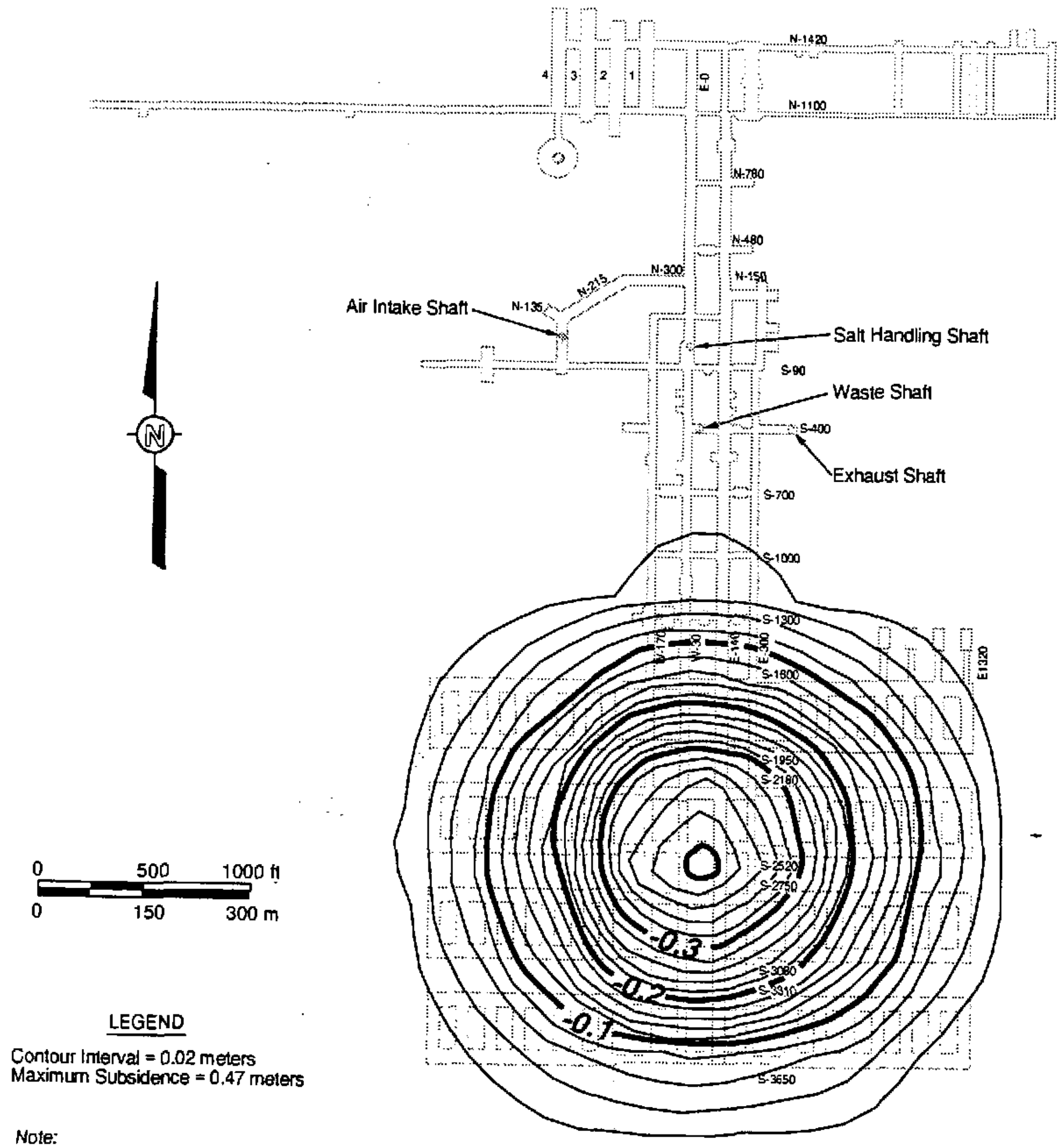
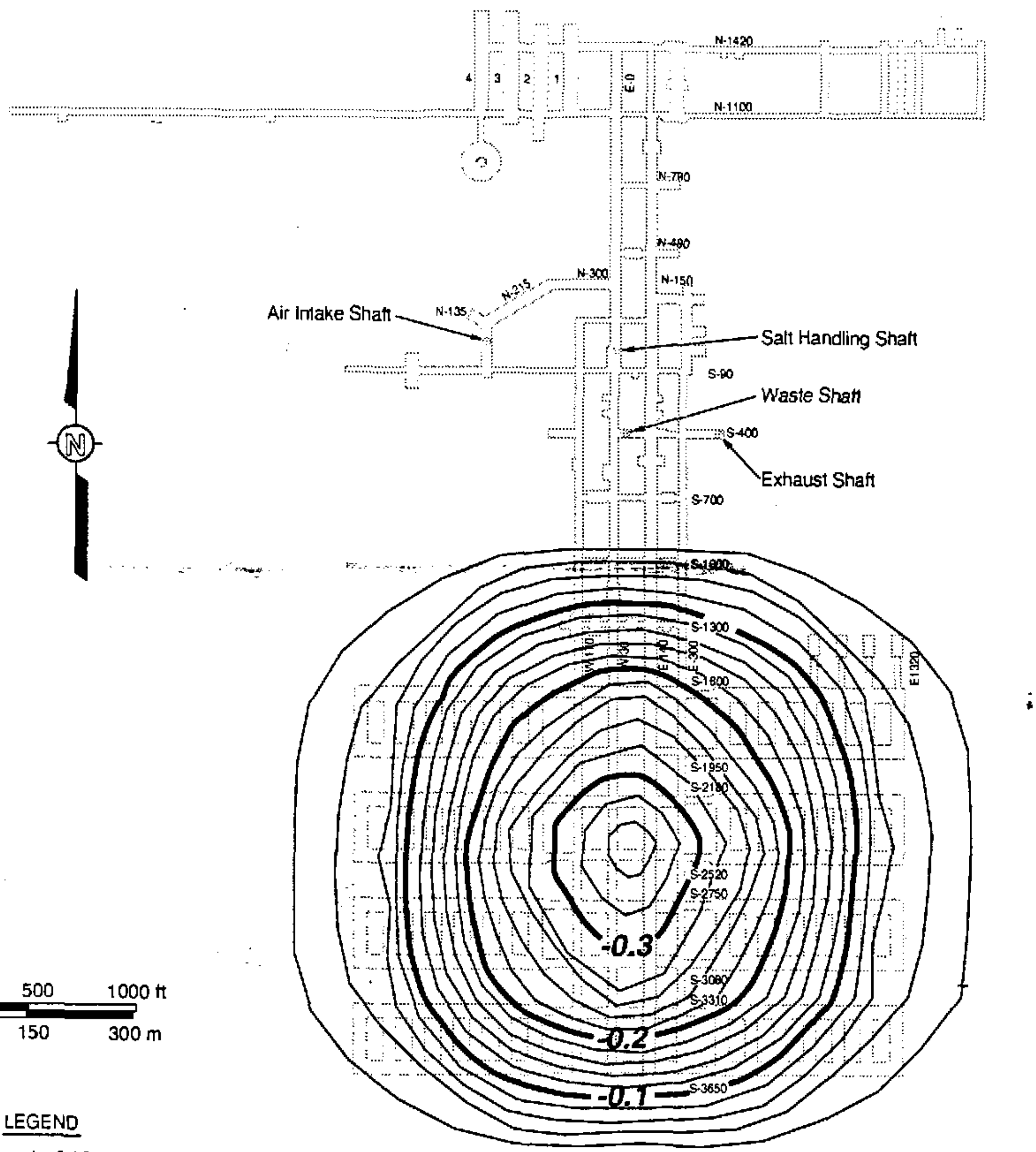


Note:
Present surface topography in this area varies by more than 3 meters. Subsidence will not create a basin and should not be visible.

Figure 3-20
Contour Plot of Maximum Expected Surface Subsidence at the WIPP Site —National Coal Board (NCB) Method (Loose Backfill All Areas)



LEGEND

Contour Interval = 0.02 meters
Maximum Subsidence = 0.44 meters

Note:
Present surface topography in this area varies by more than 3 meters. Subsidence will not create a basin and should not be visible.

Figure 3-21
Contour Plot of Maximum Surface Subsidence at the WIPP Site —National Coal Board (NCB) Method (Compacted Backfill in All Areas)

301699.09/tld A25 7/13/94

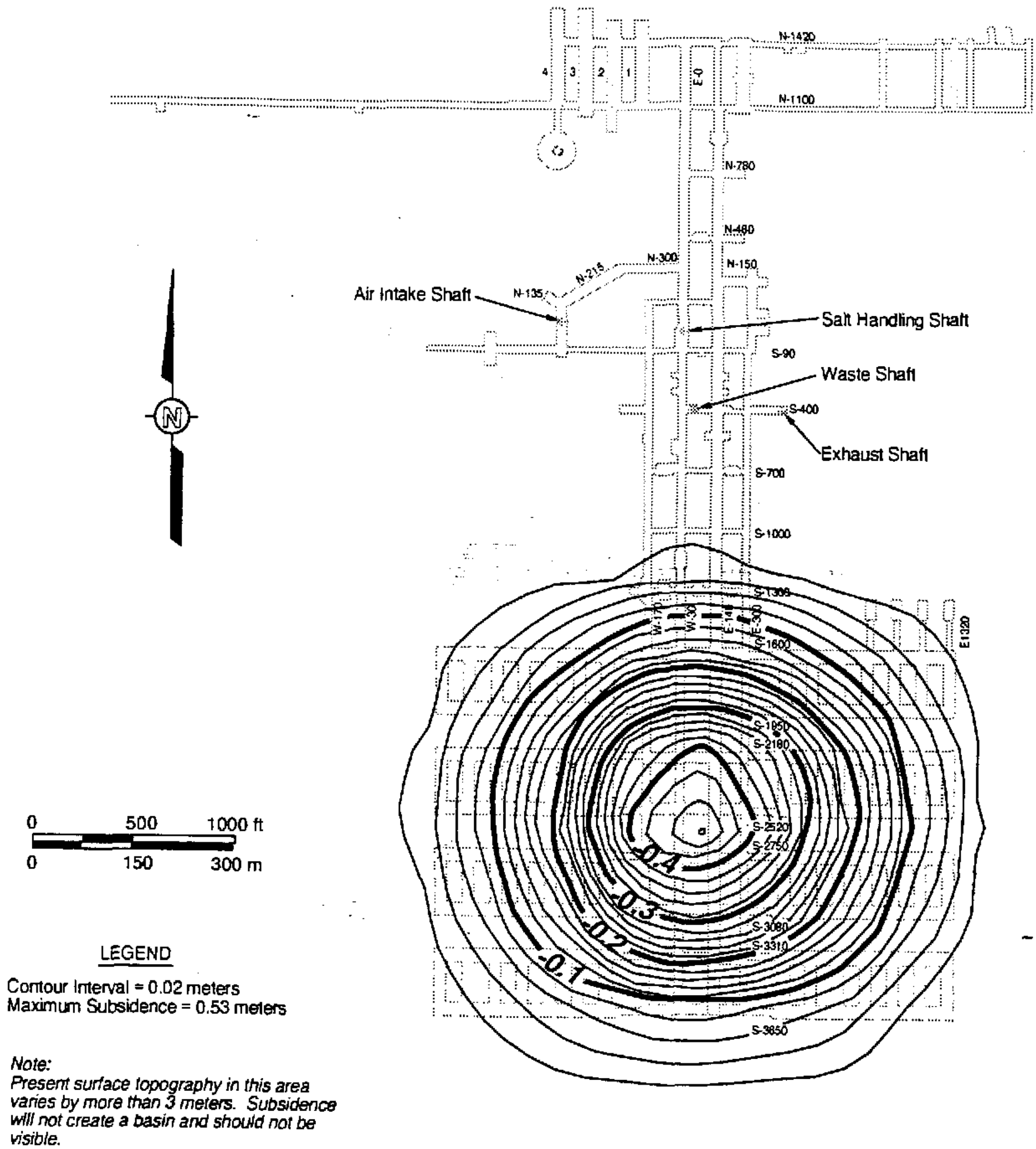


Figure 3-22
Contour Plot of Maximum Expected Surface Subsidence at the WIPP Site —National Coal Board (NCB) Method (Waste Only in Waste Emplacement Area; Compacted Backfill in Other Areas)

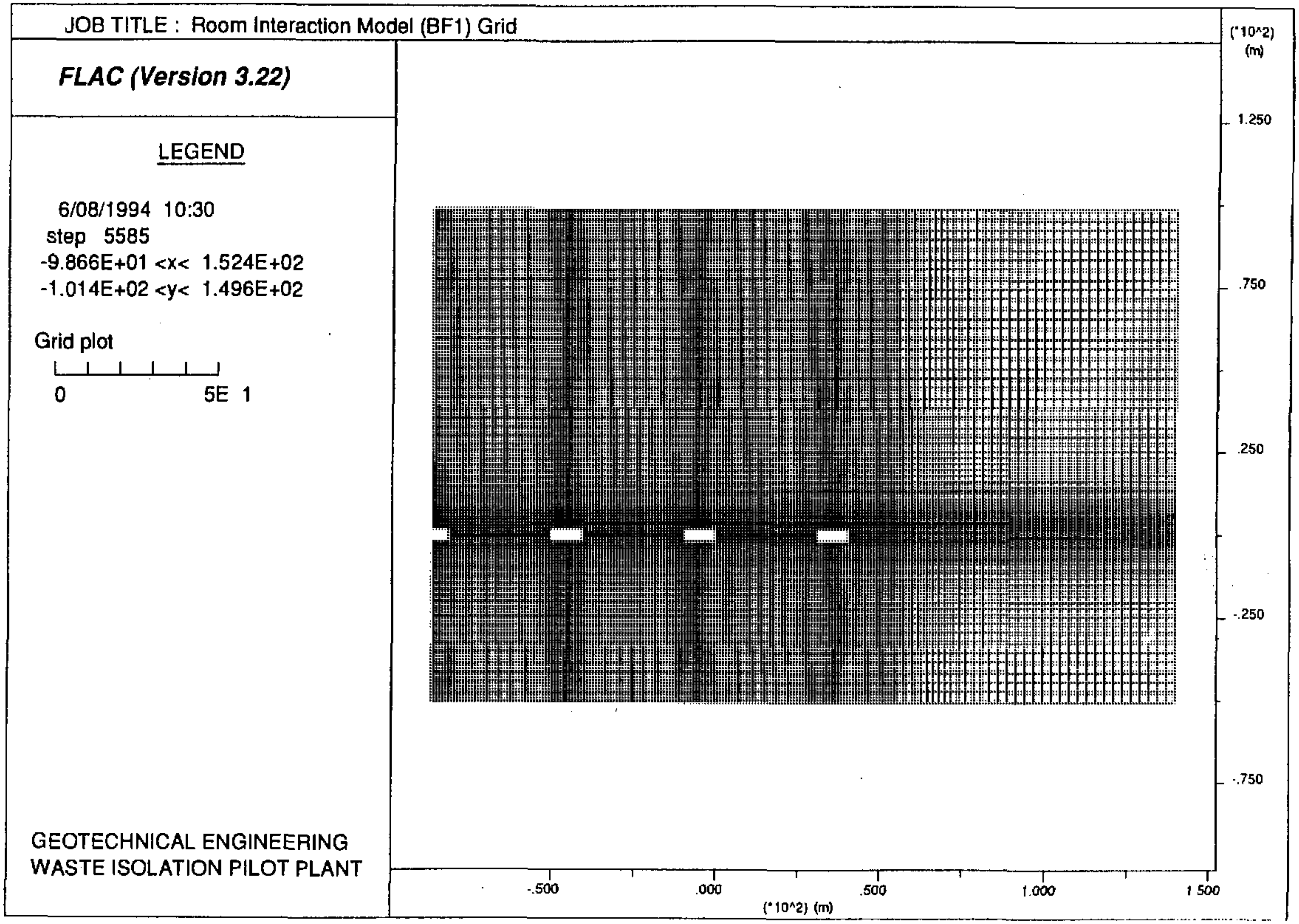


Figure 3-23
Room Interaction Model Grid

301699.09/cw A70

6/21/94

301699.09/cw A64

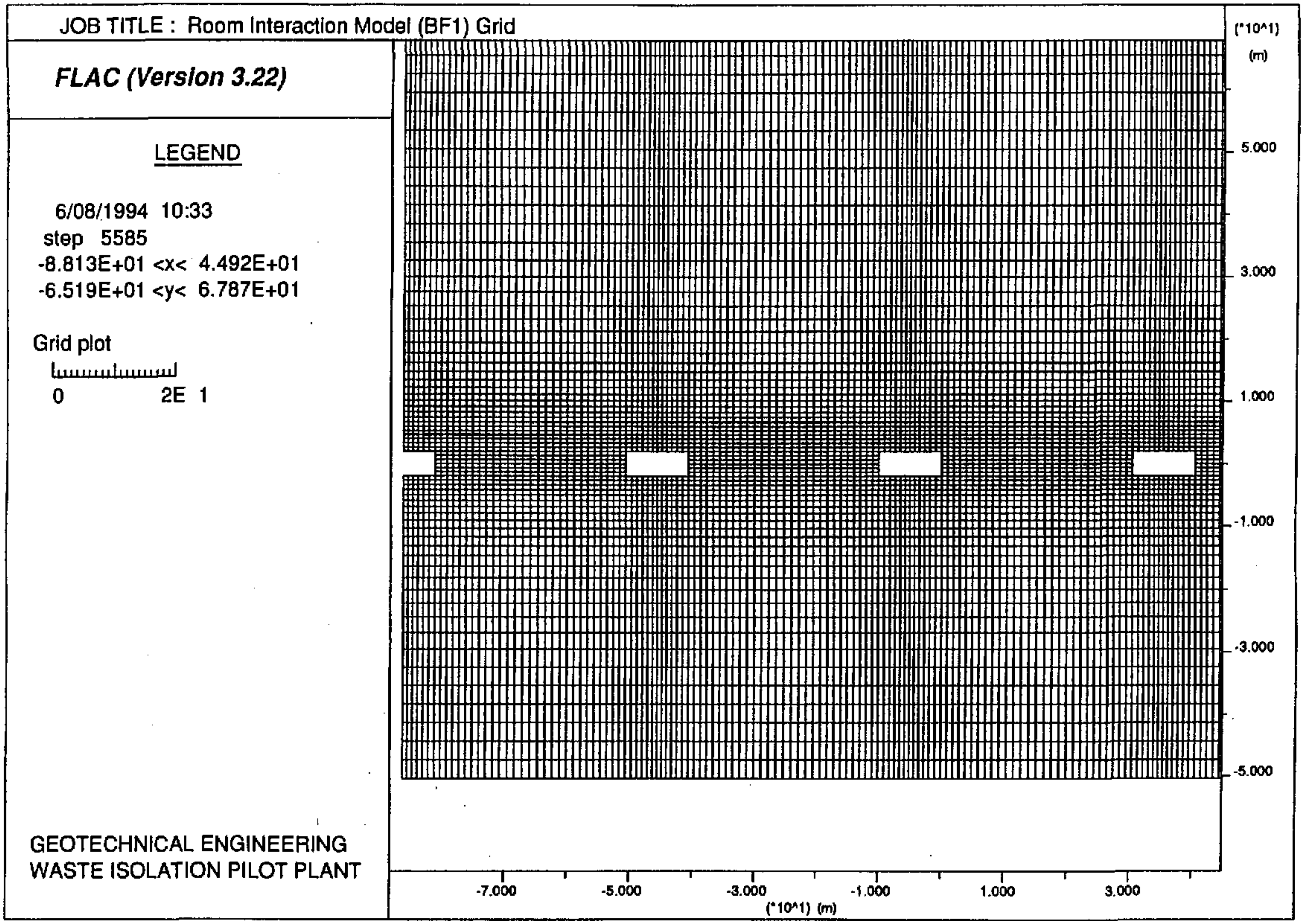


Figure 3-24
Room Interaction Model Grid Detail

6/21/94

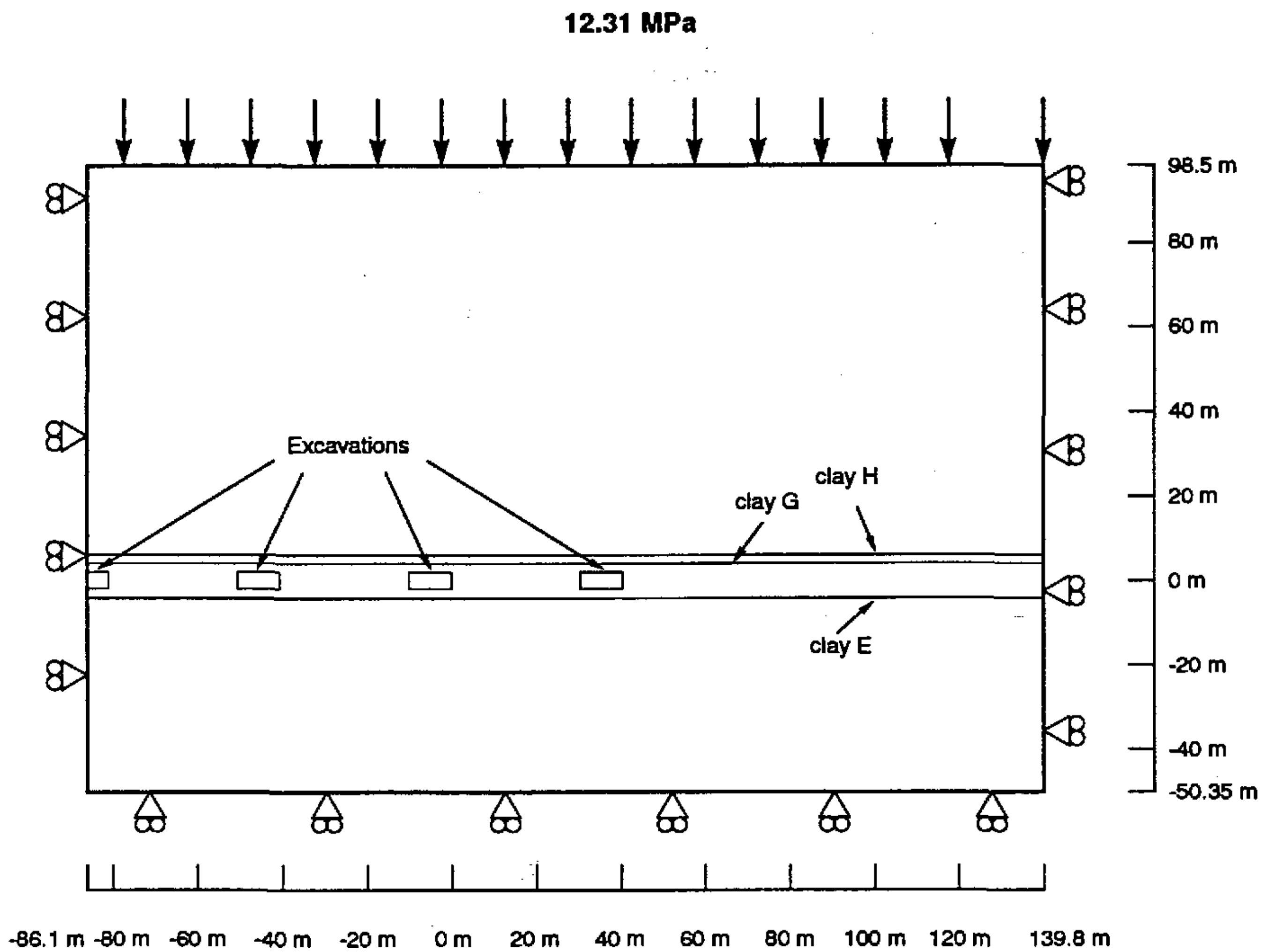


Figure 3-25
Room Interaction Model Boundary Conditions

301699.09/cw A65

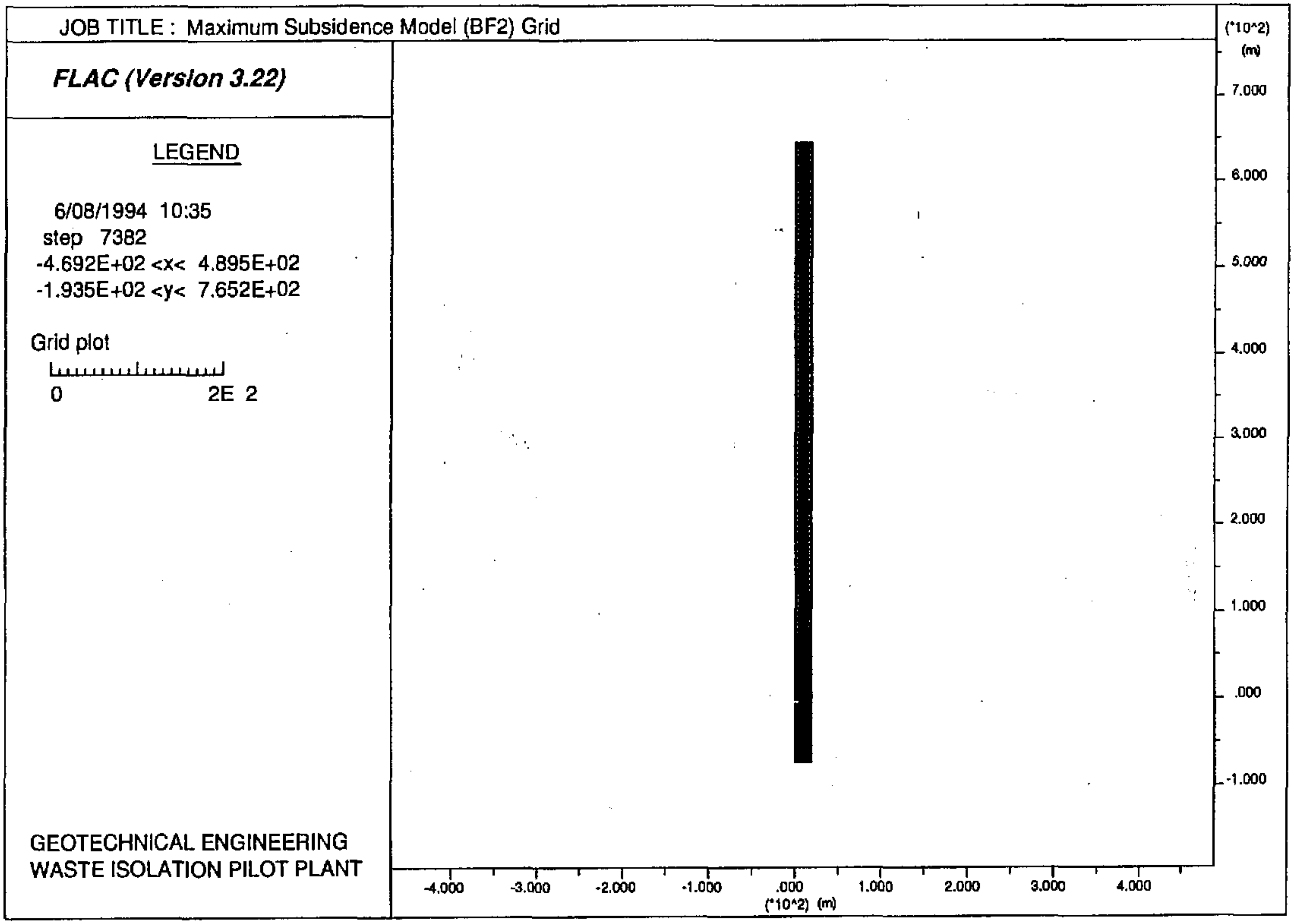


Figure 3-26
Maximum Subsidence Model Grid

6/21/94

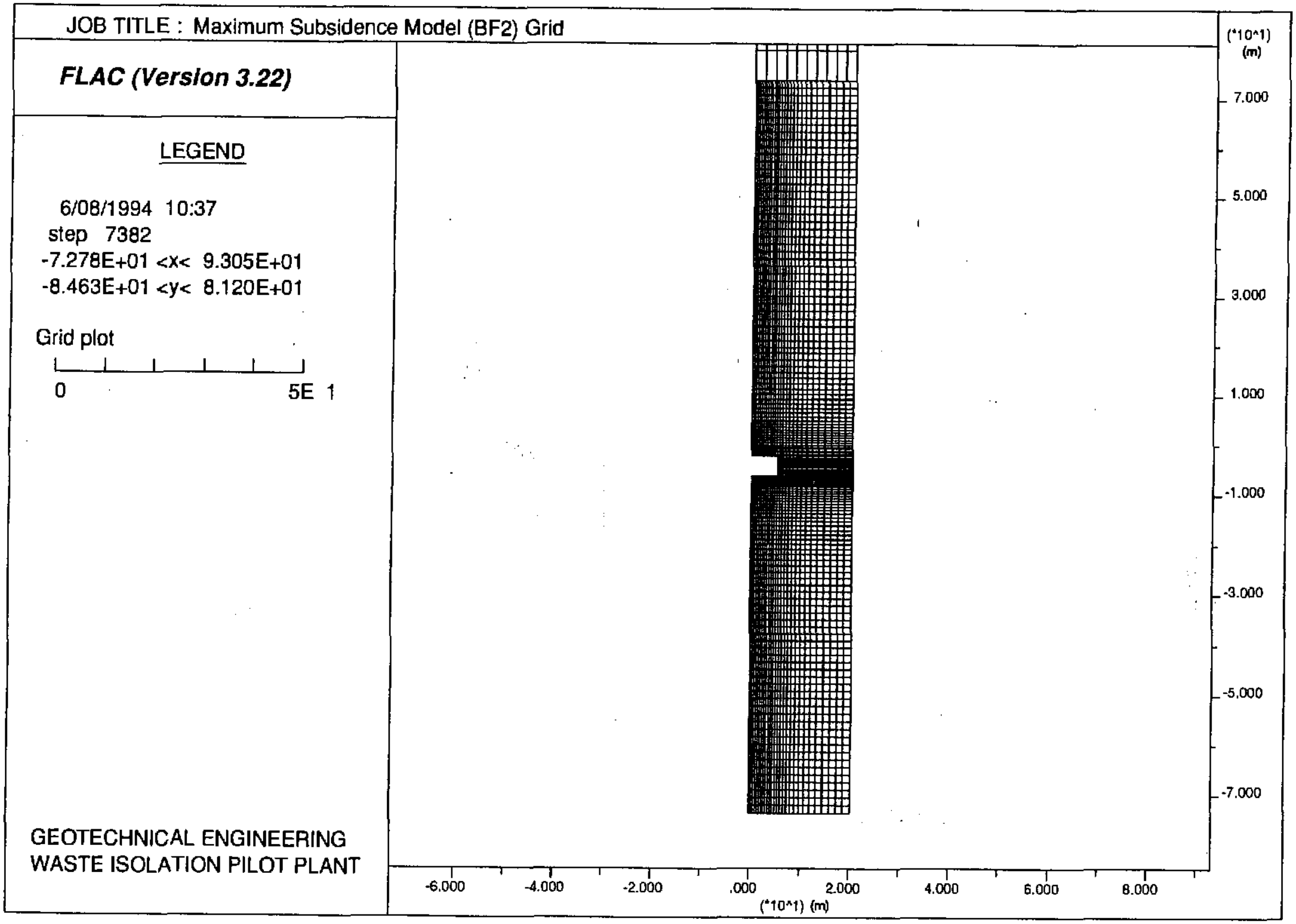


Figure 3-27
Maximum Subsidence Model Grid Detail 1

301695.09/cw A66

6/21/94

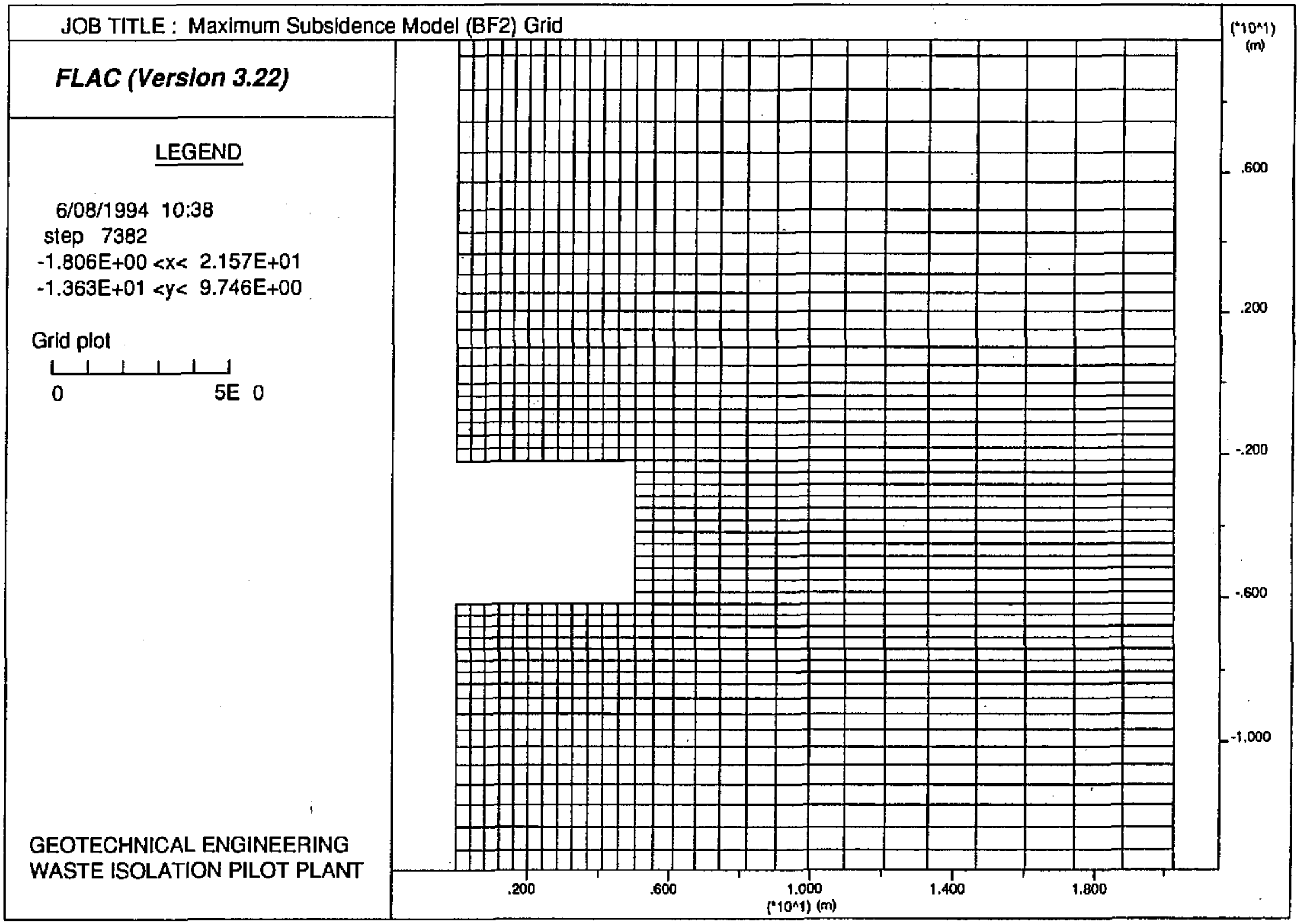


Figure 3-28

Maximum Subsidence Model Grid Detail 2

301699.09/cw A67

6/21/94

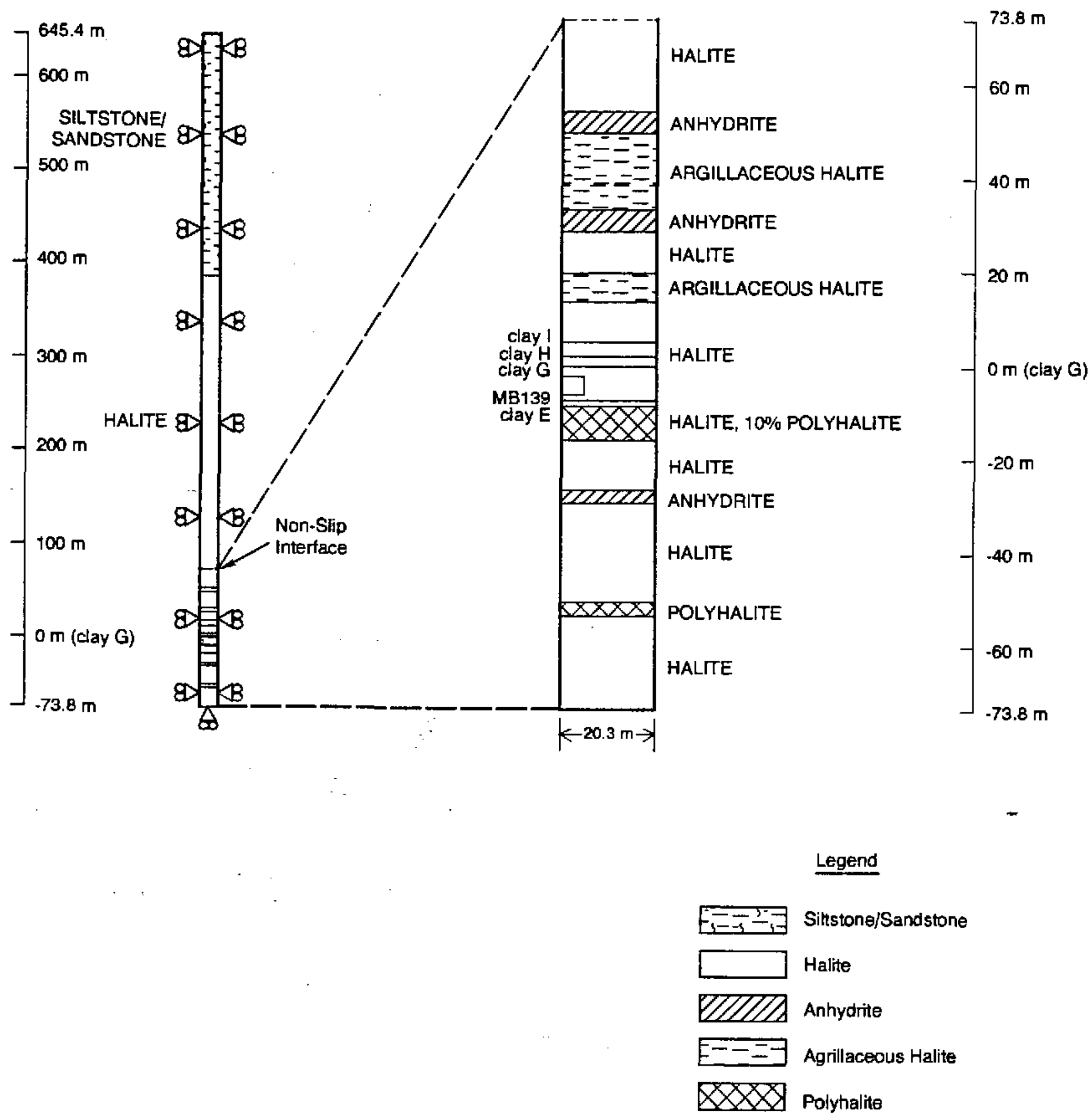


Figure 3-29
Maximum Subsidence Model Boundary Conditions and Stratigraphy

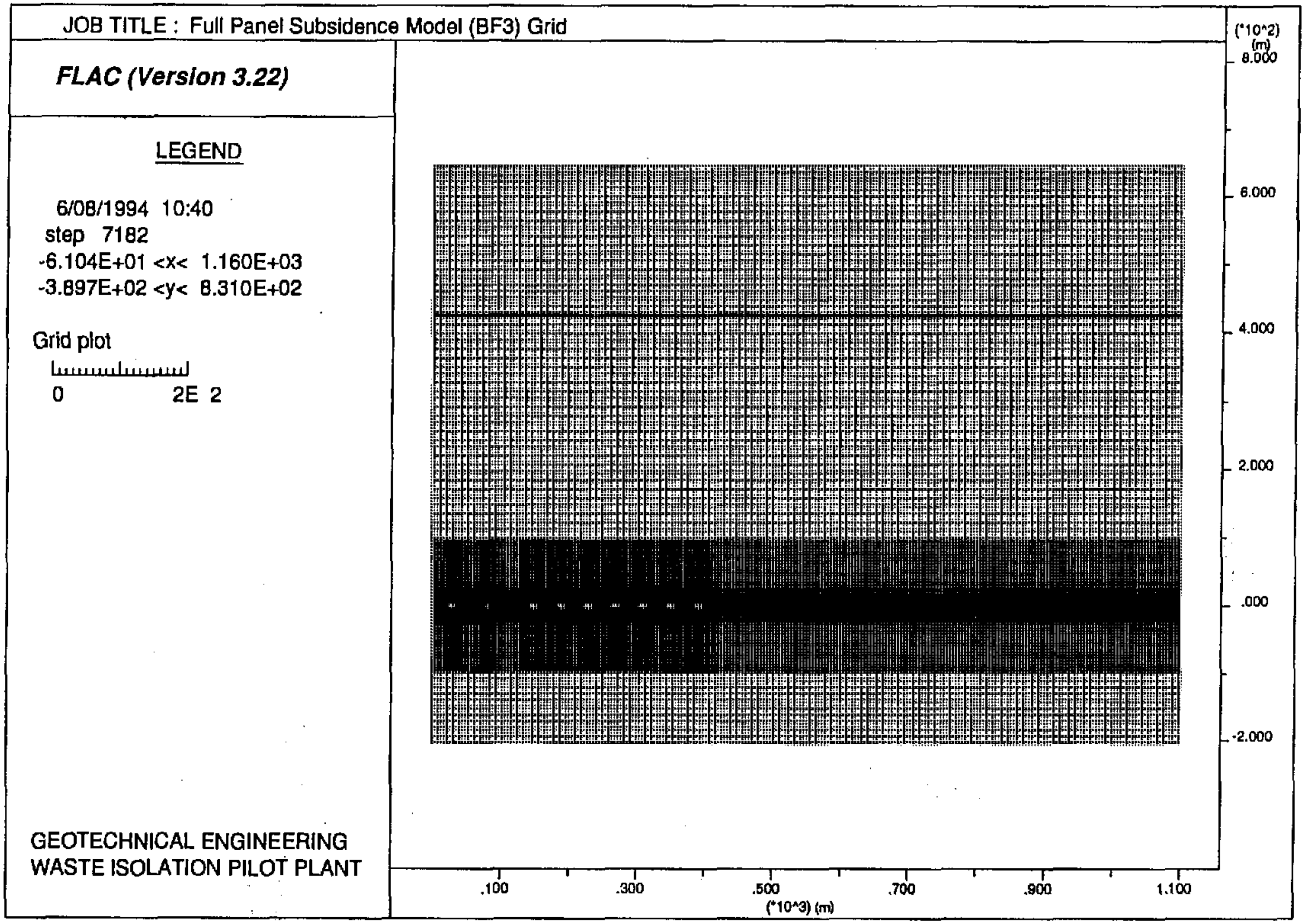


Figure 3-30
Full Panel Subsidence Model Grid

301699.09/cw A69

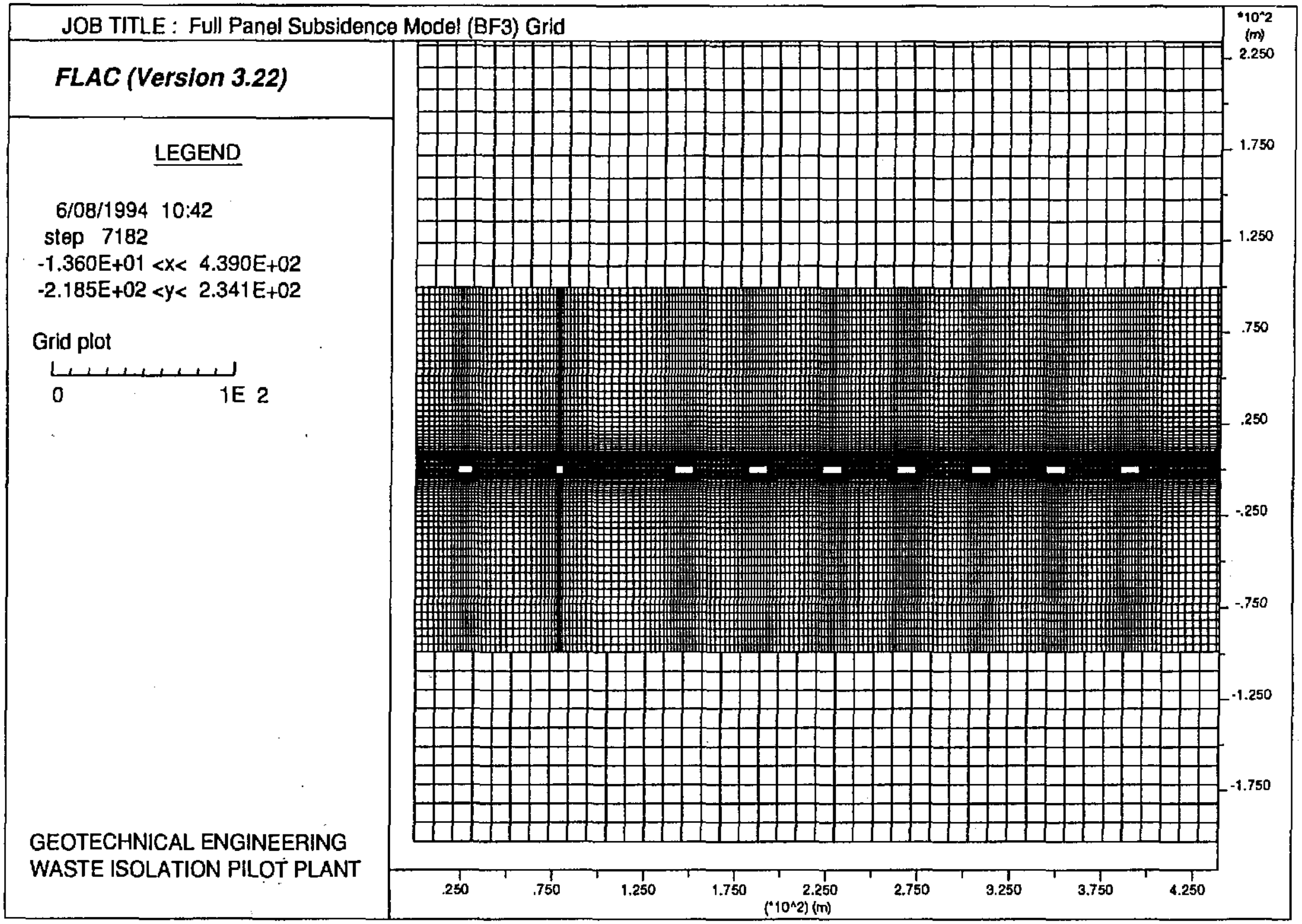


Figure 3-31
Full Panel Subsidence Model Grid Detail

6/21/94

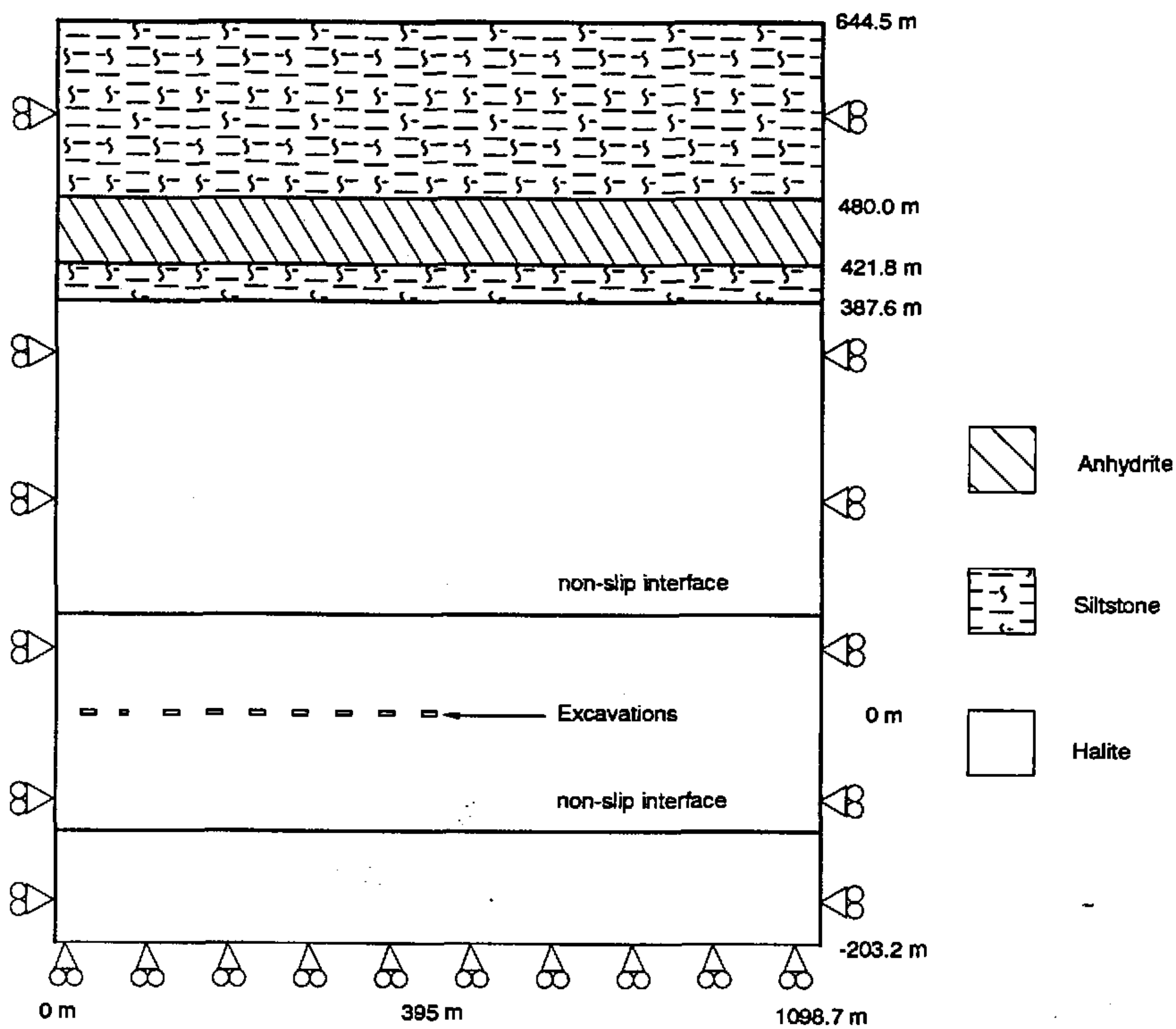


Figure 3-32
Full Panel Subsidence Model Boundary Conditions and Stratigraphy

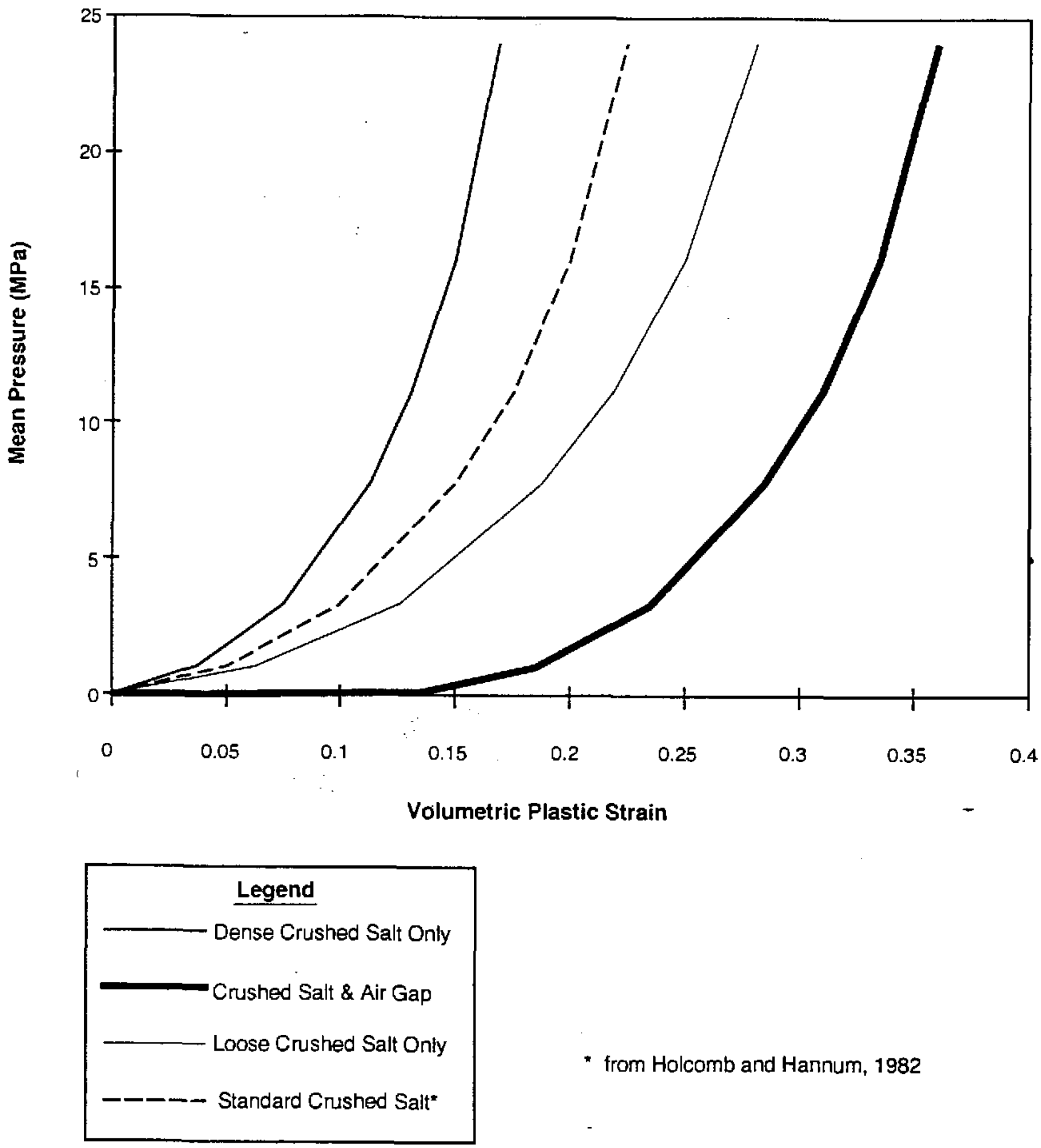
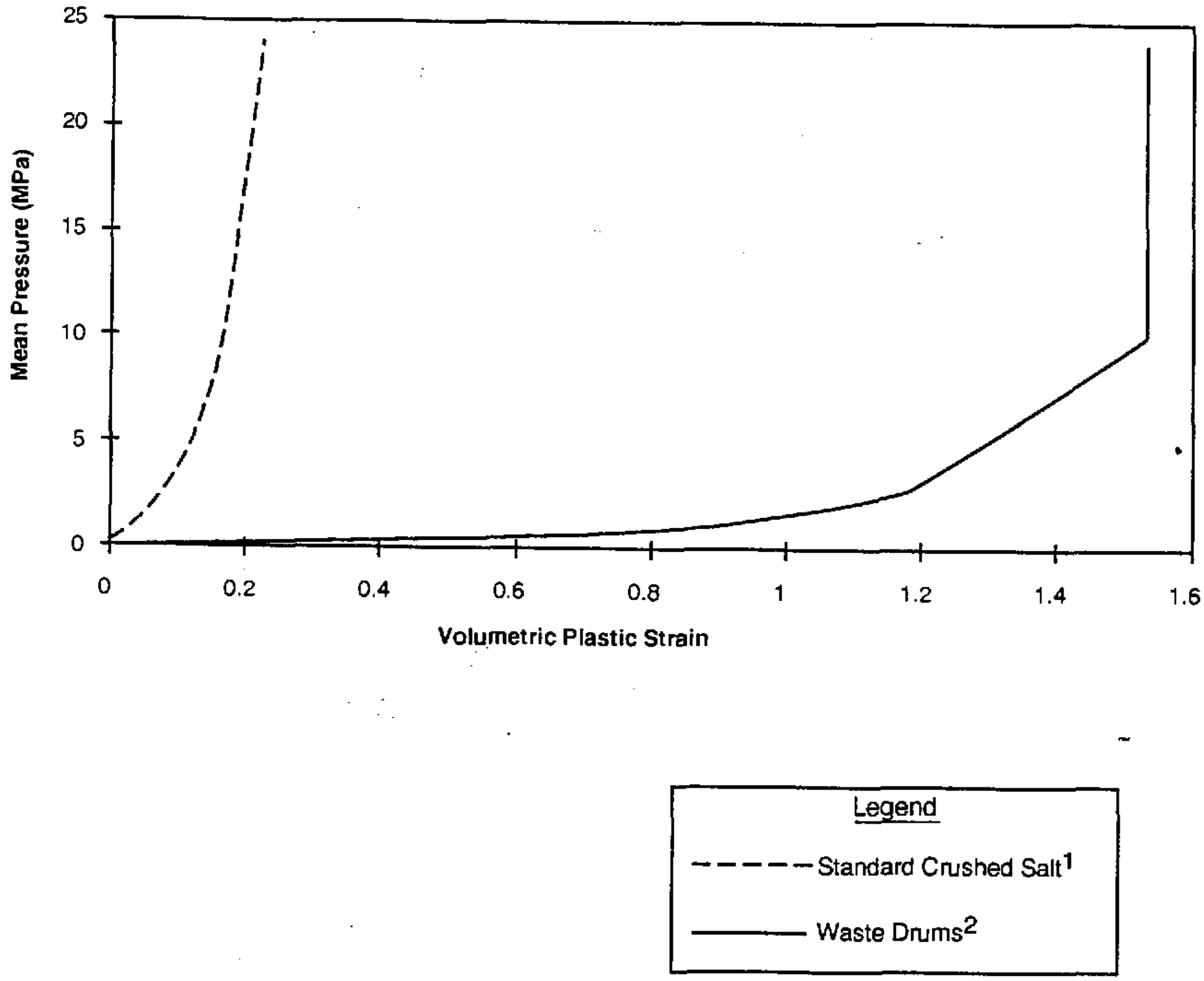


Figure 3-33
Backfill Consolidation Curves for FLAC Models



[1] *Holcomb and Hannum, 1982*

[2] *Butcher and Mendenhall, 1993*

Figure 3-34
CH-TRU Waste Drum Consolidation Curve for FLAC Models

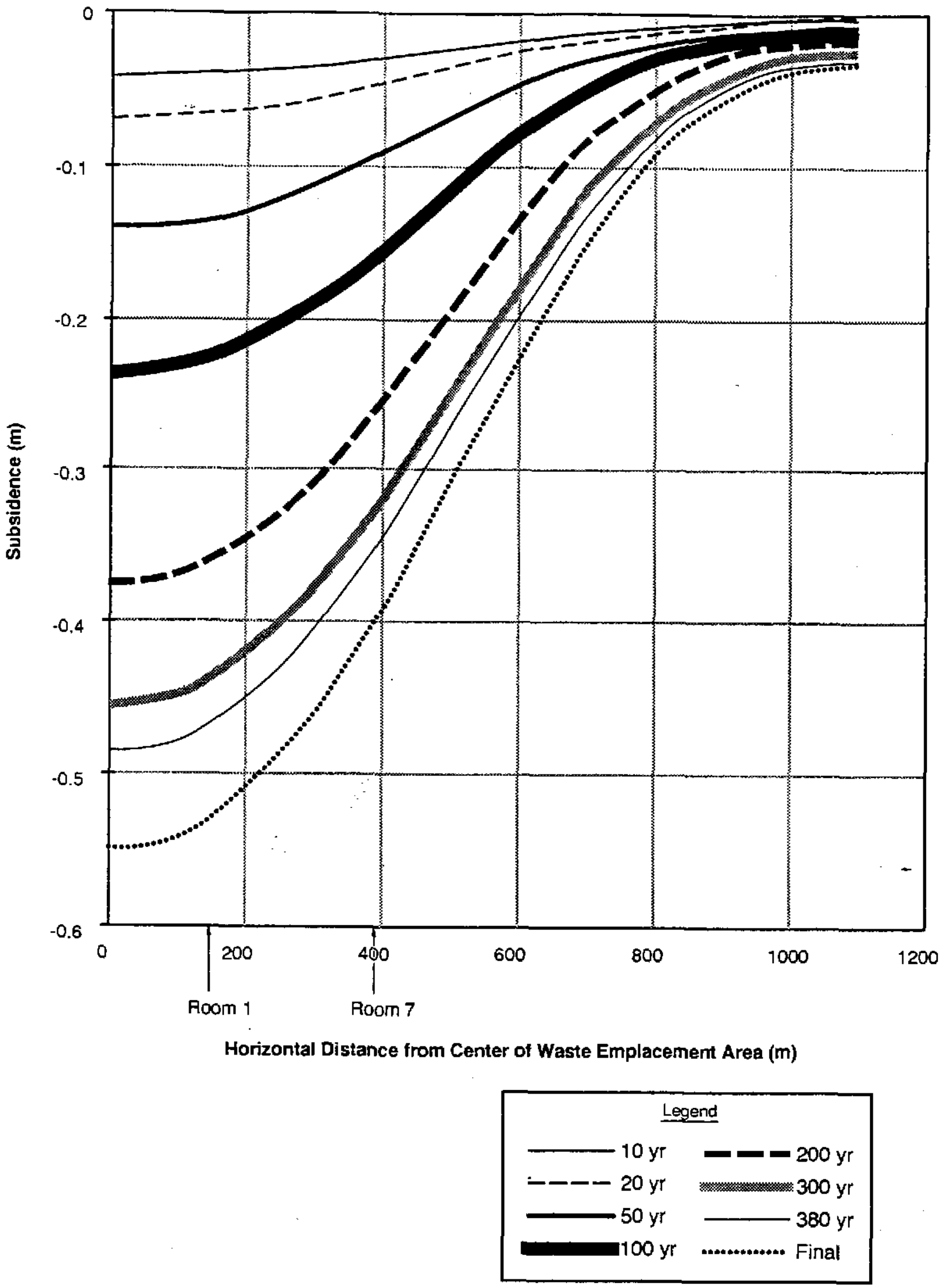


Figure 3-35
Subsidence Profile at Surface—
Full Panel FLAC Backfill Model

301699.09/cw A49

6/8/94

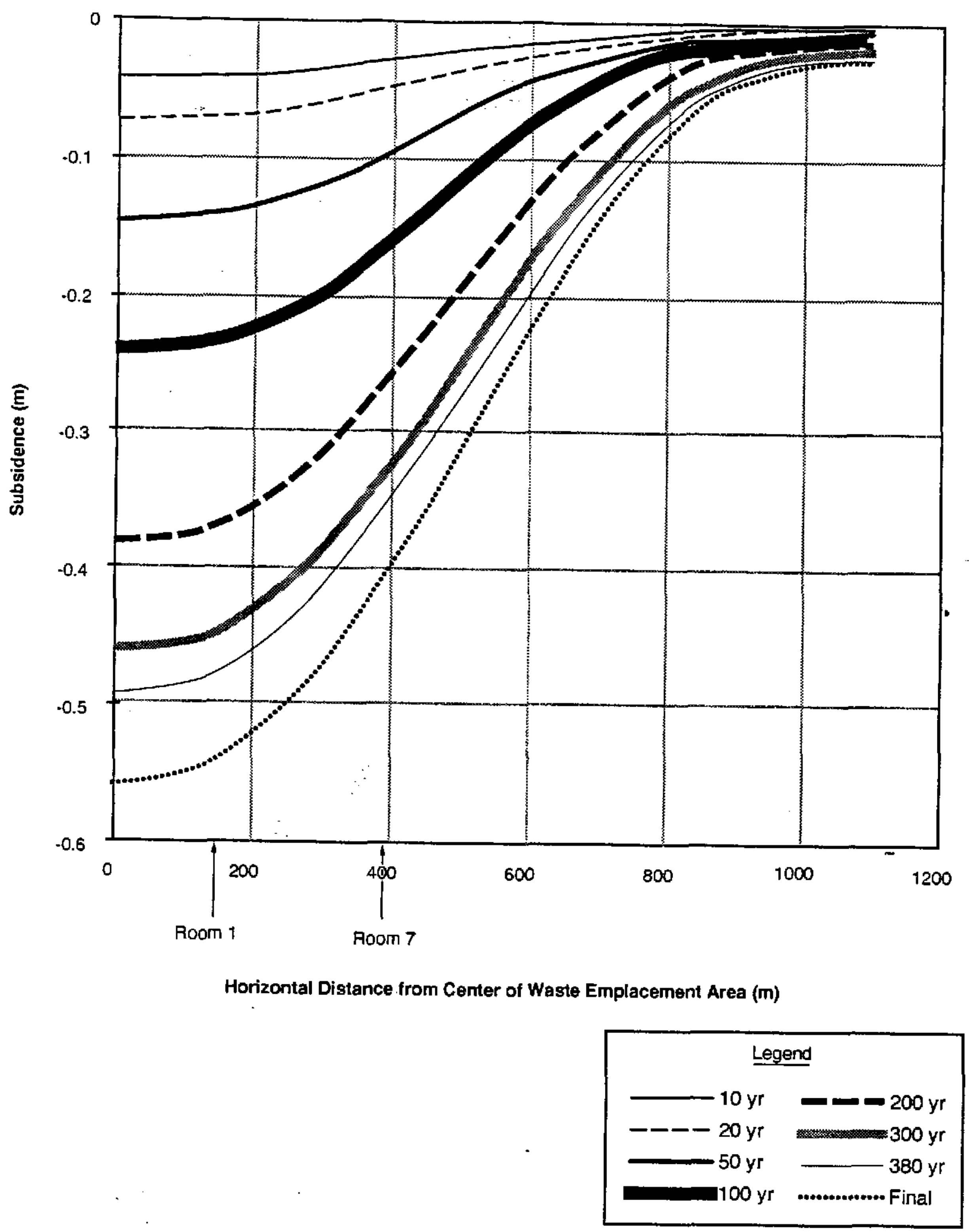


Figure 3-36
Subsidence Profile at Culebra Dolomite Level—
Full Panel FLAC Backfill Model

301699.09/cw A35

6/8/94

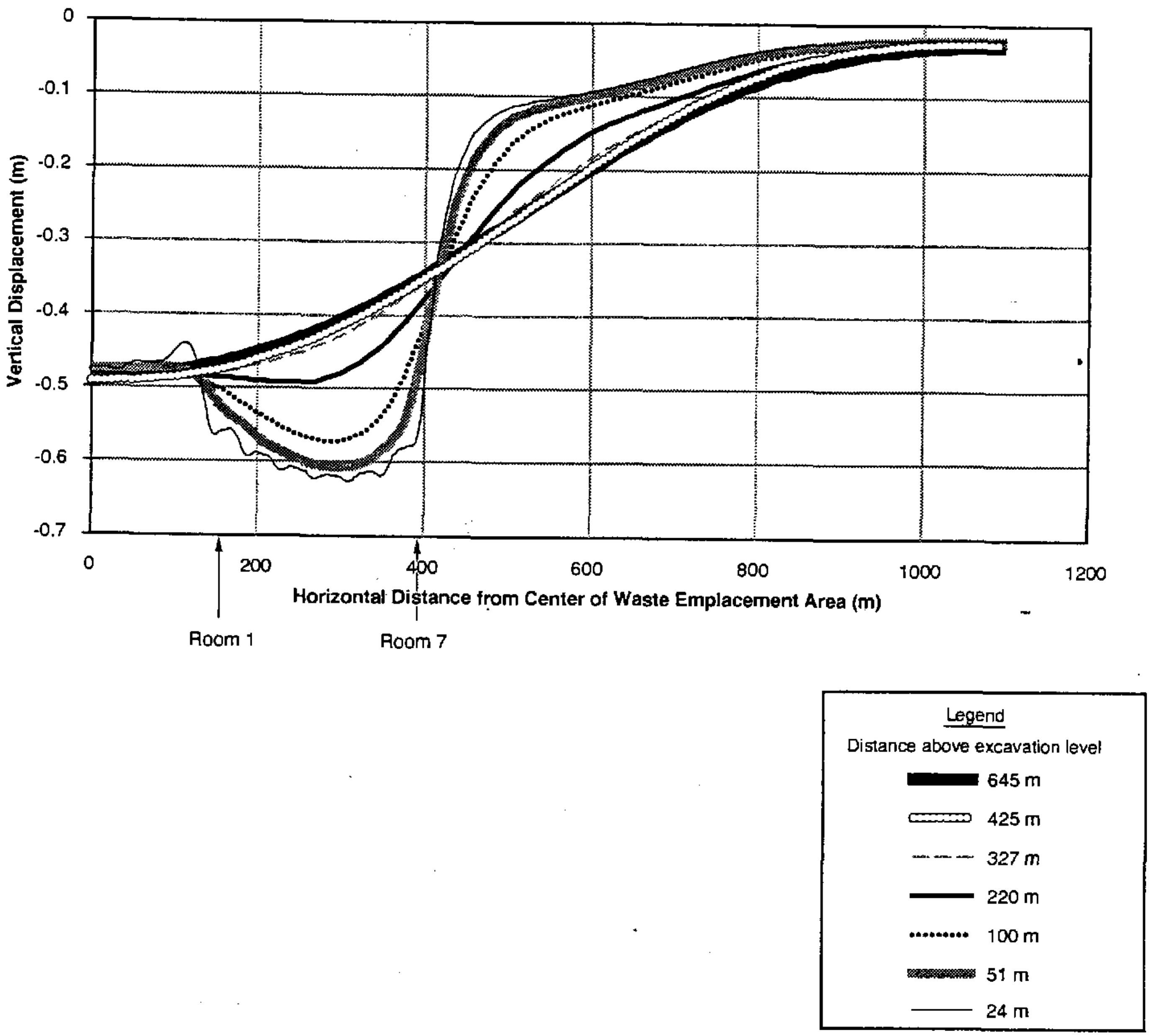


Figure 3-37
Subsidence Profiles at Various Depths

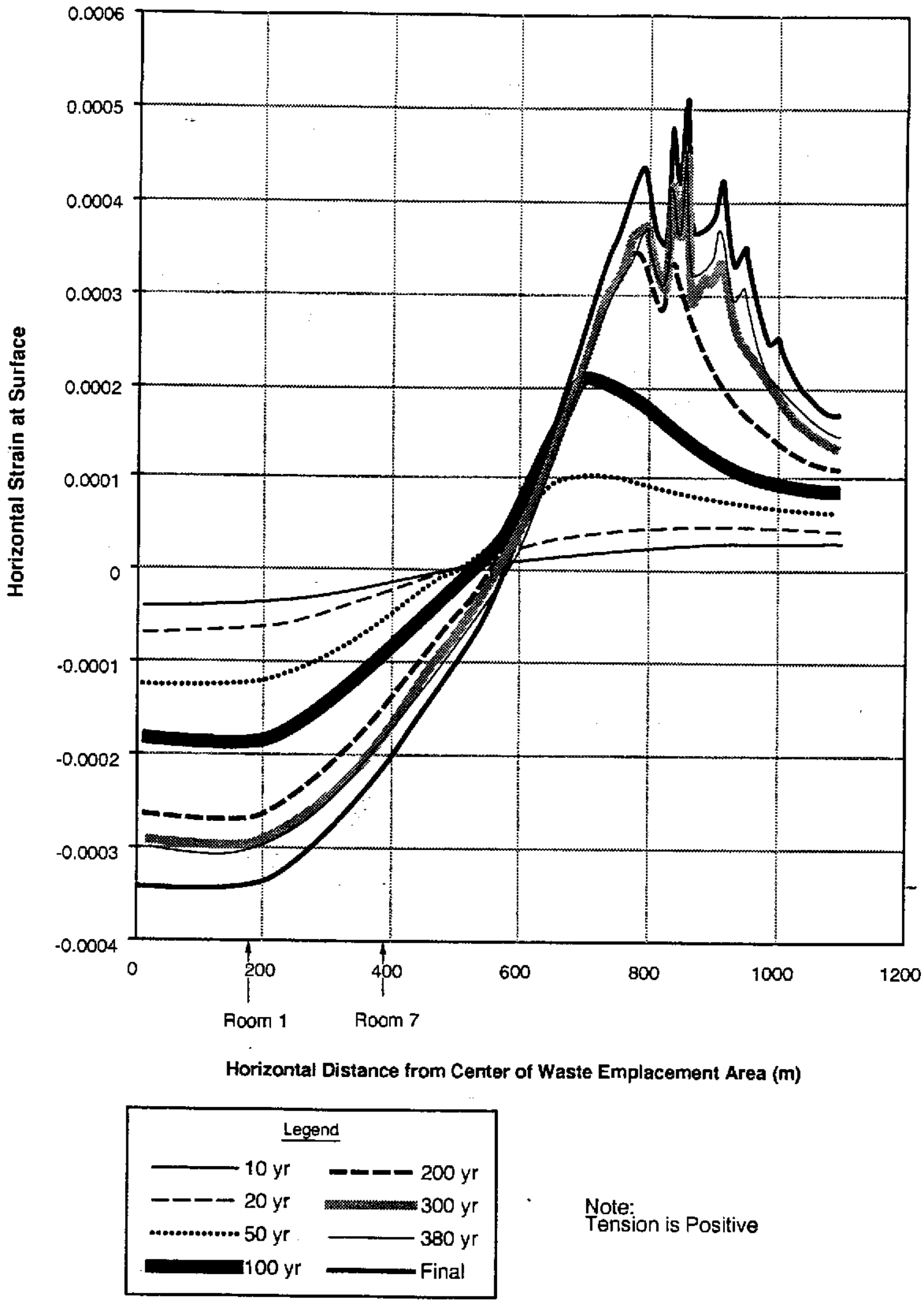


Figure 3-38
Horizontal Strain Profile at Surface—
Full Panel FLAC Backfill Model

301699.09/cw A38

6/8/94

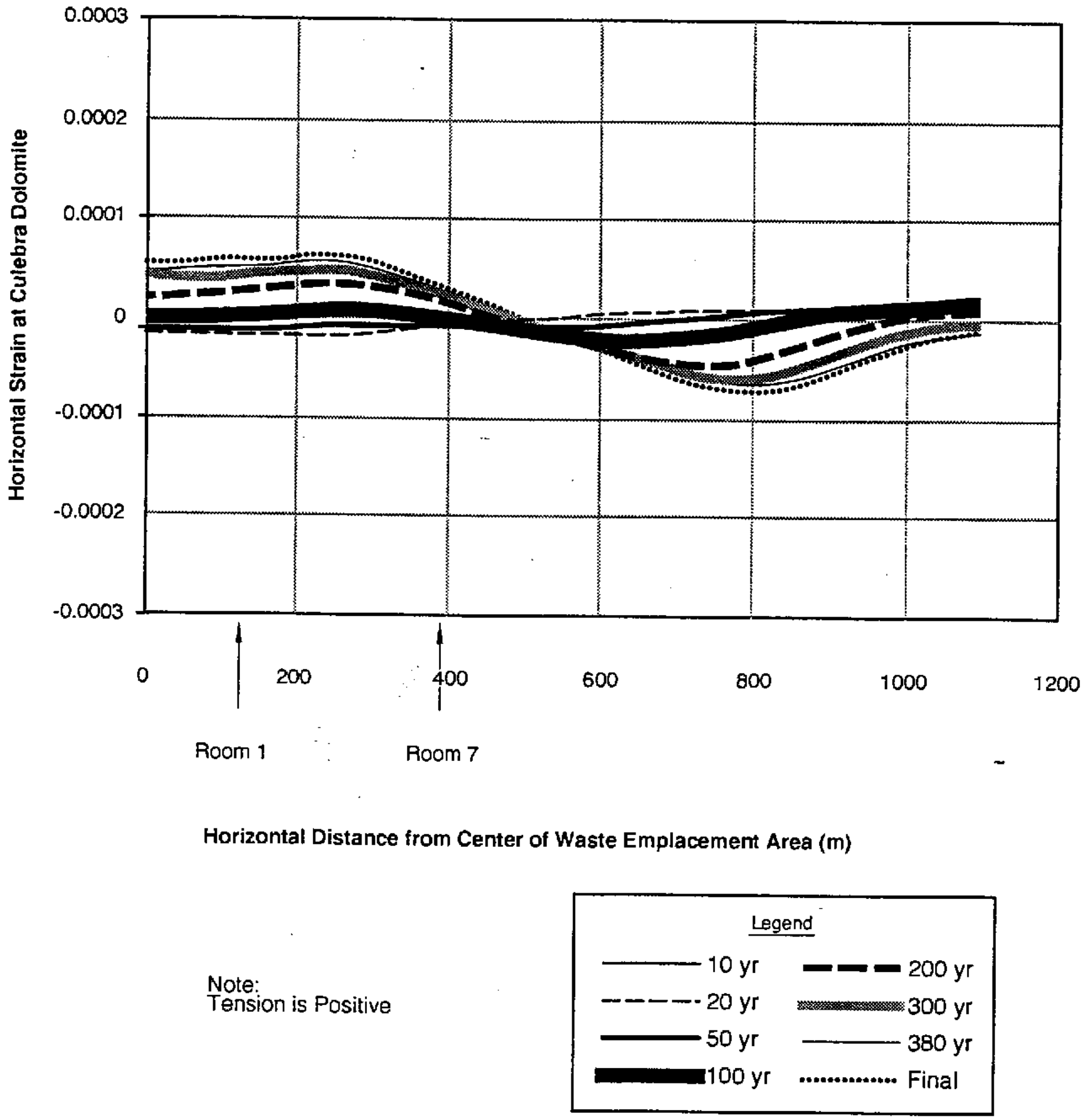


Figure 3-39
Horizontal Strain Profile at Culebra Dolomite Level—
Full Panel FLAC Backfill Model

301699.09/cw A37

6/8/94

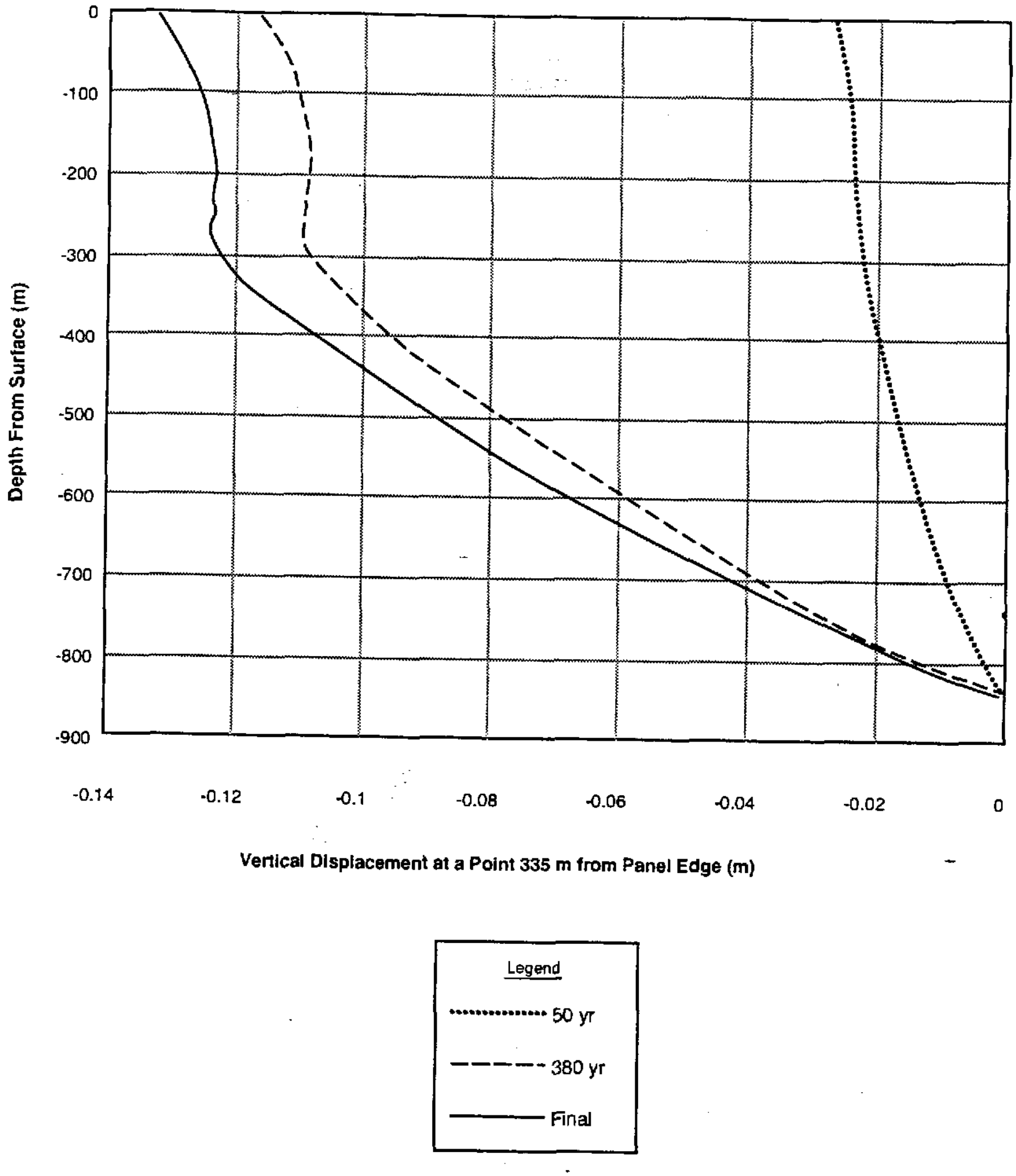


Figure 3-40
Vertical Displacement Profile at Approximate Shaft Location—
Full Panel FLAC Backfill Model

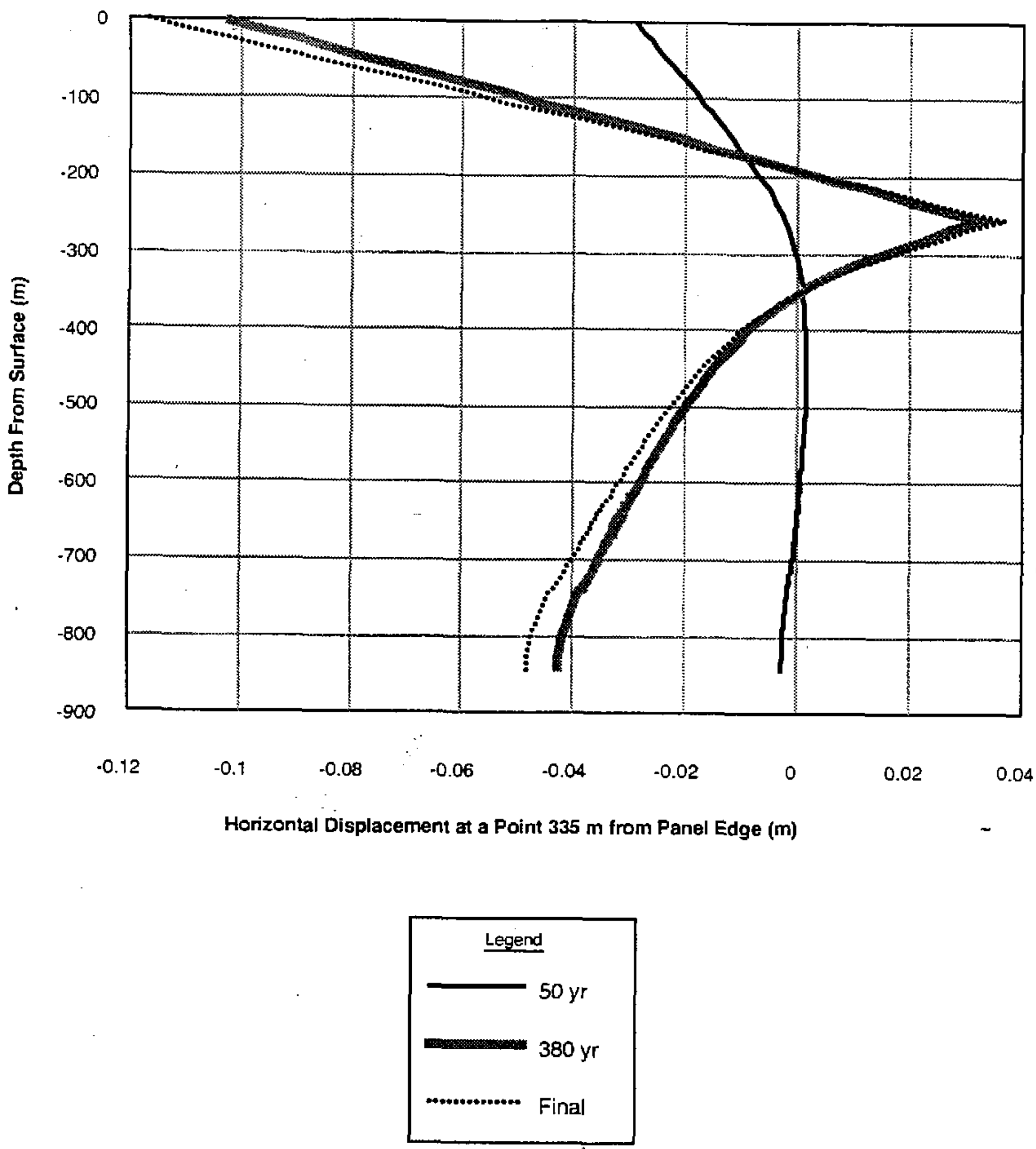


Figure 3-41
Horizontal Displacement at Approximate Shaft Location—
Full Panel FLAC Backfill Model

301699.09/cw A40

6/10/94

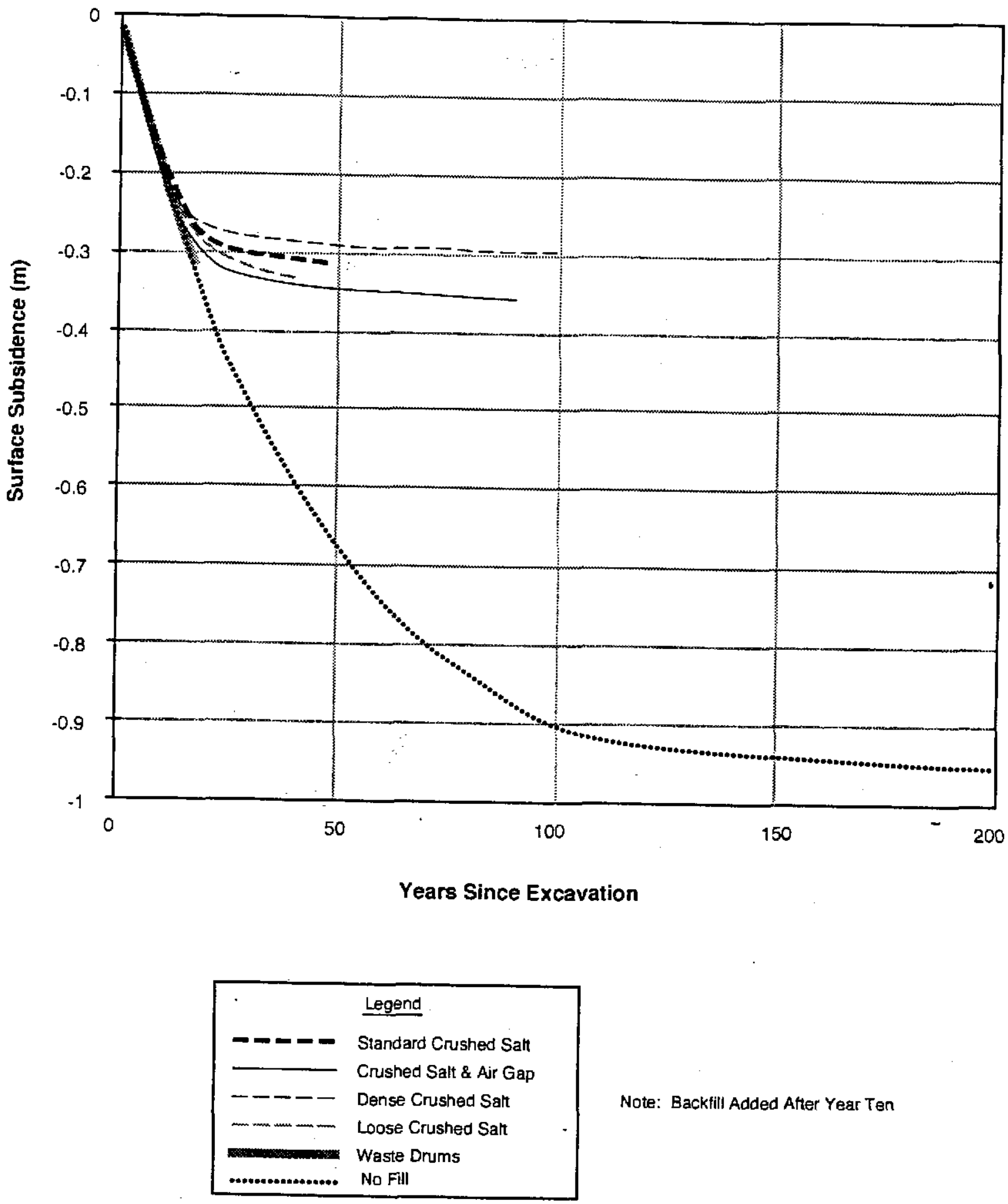


Figure 3-42
Subsidence Magnitude for Various Backfill Types—Single Room FLAC Backfill Model

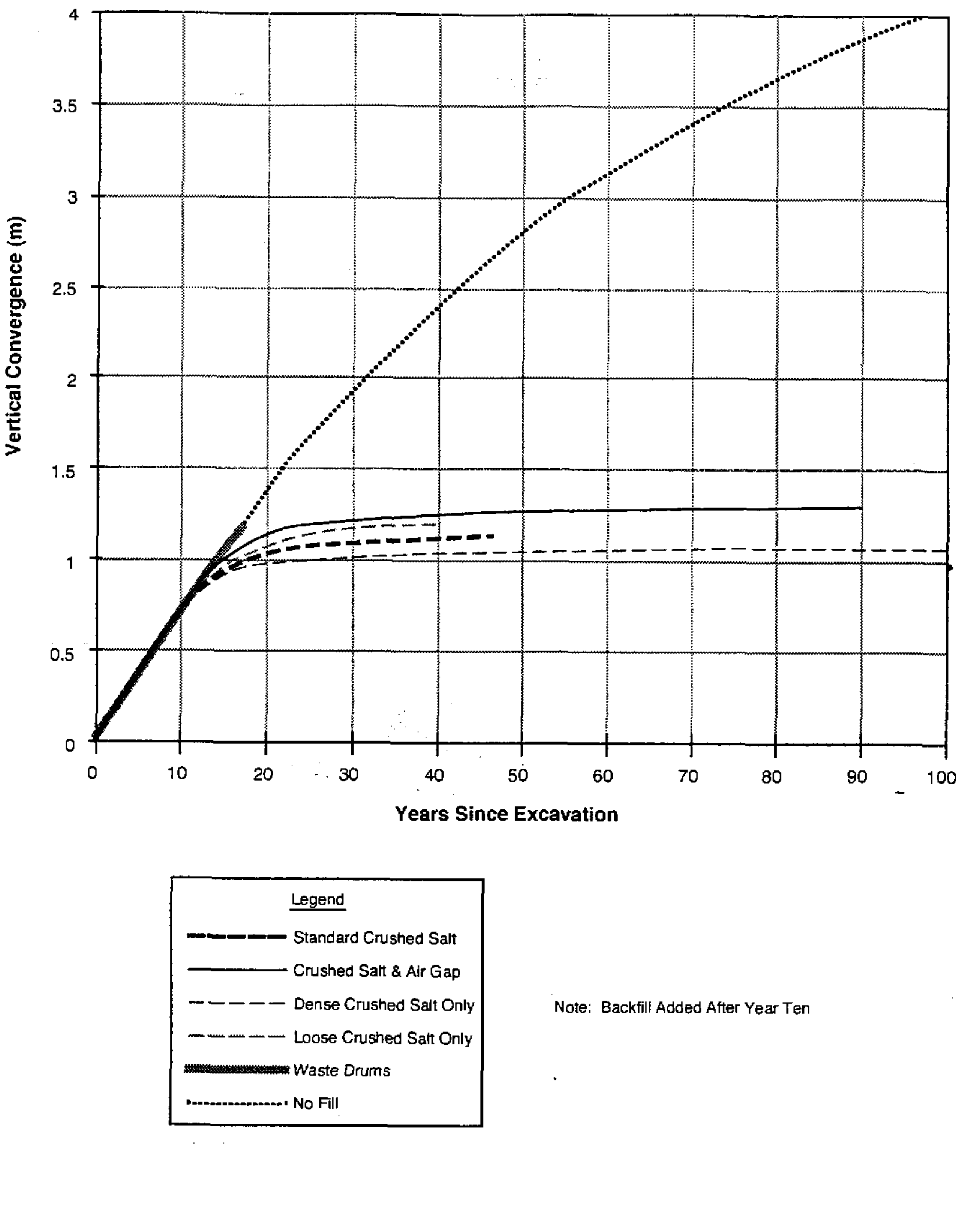
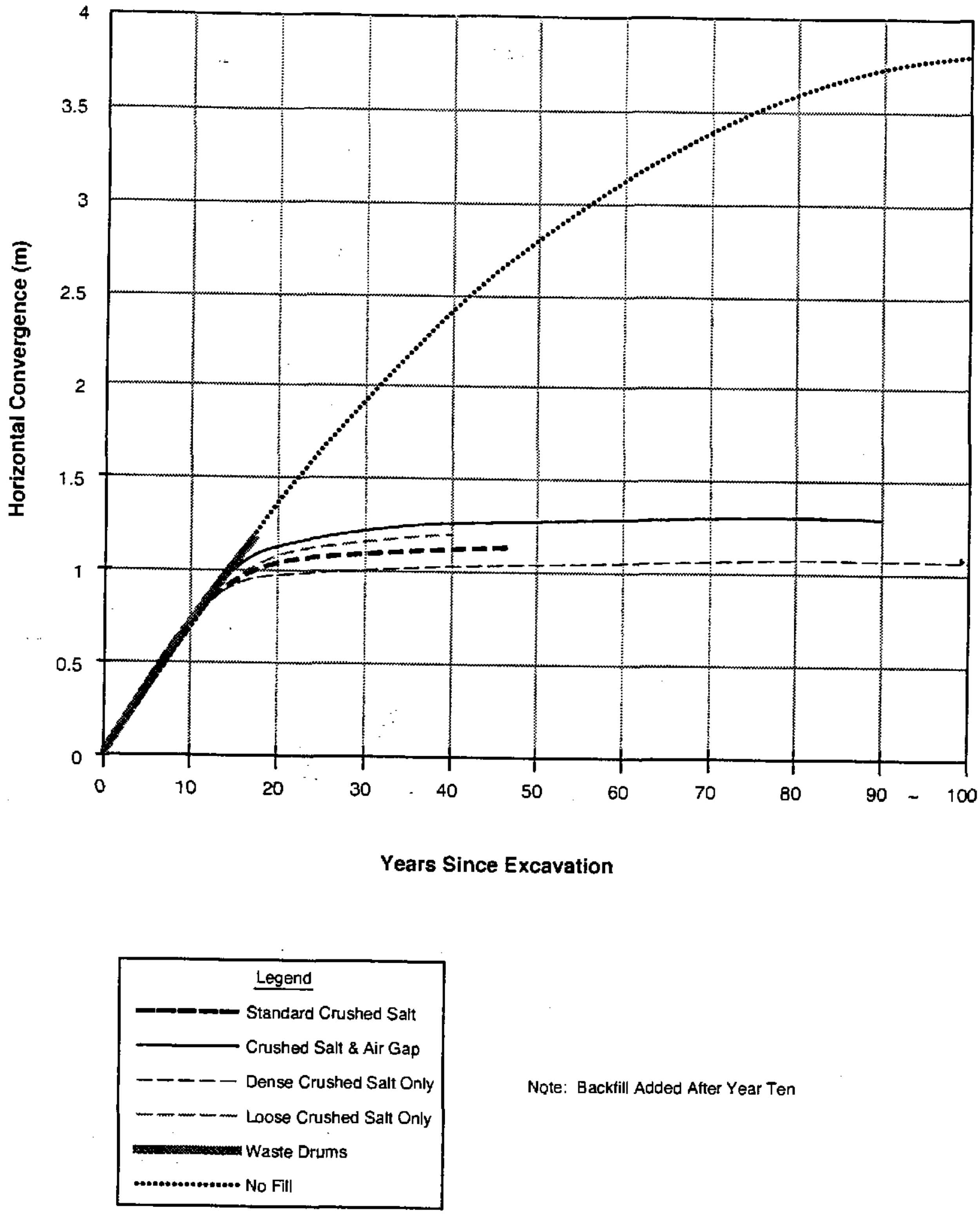


Figure 3-43
Vertical Convergence for Various Backfill Types—
Single Room FLAC Backfill Model



Note: Backfill Added After Year Ten

Figure 3-44
Horizontal Convergence for Various Backfill Types— Single Room FLAC Backfill Model

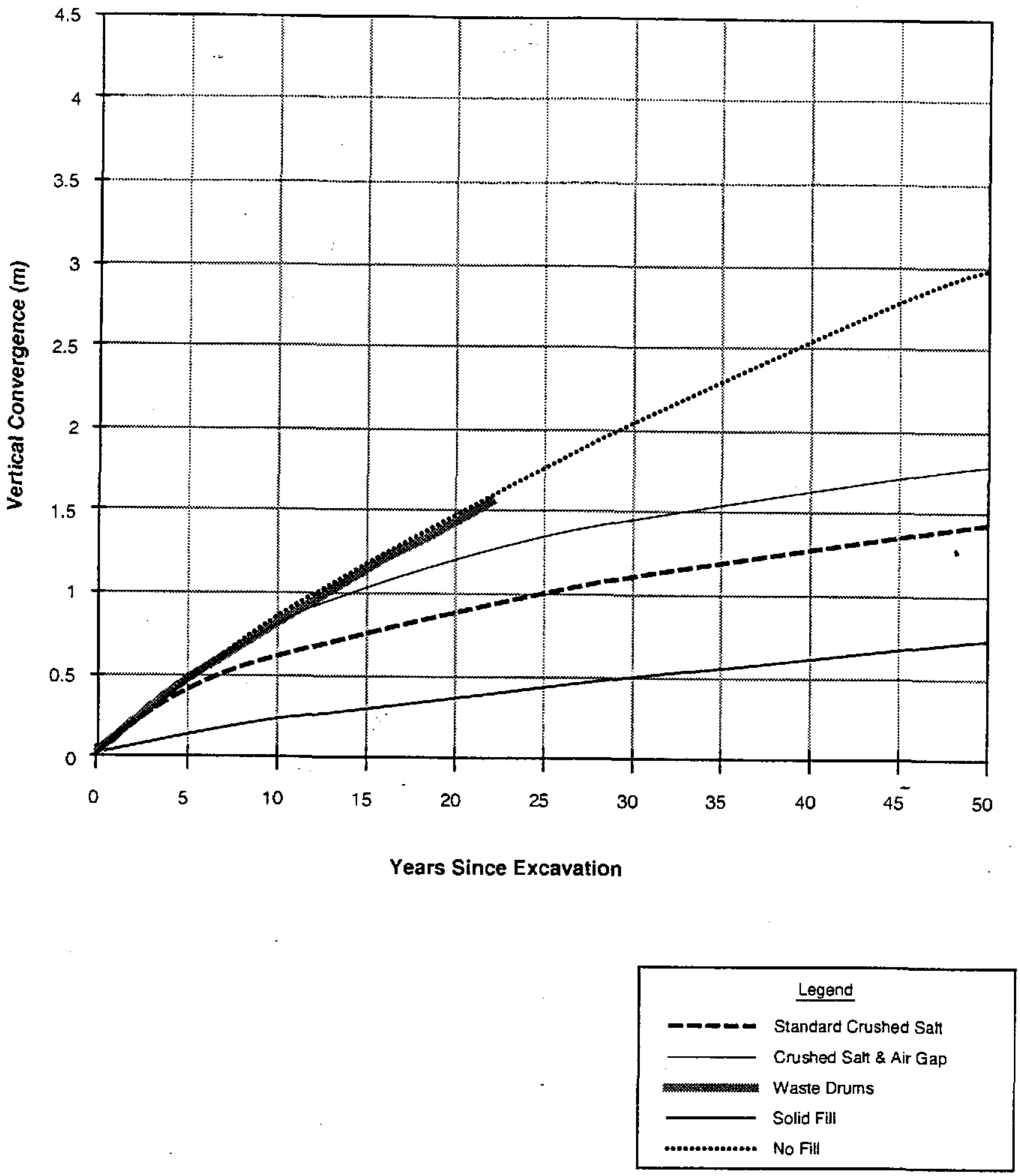


Figure 3-45
Vertical Convergence for Various Backfill Types—
Half Panel FLAC Backfill Model

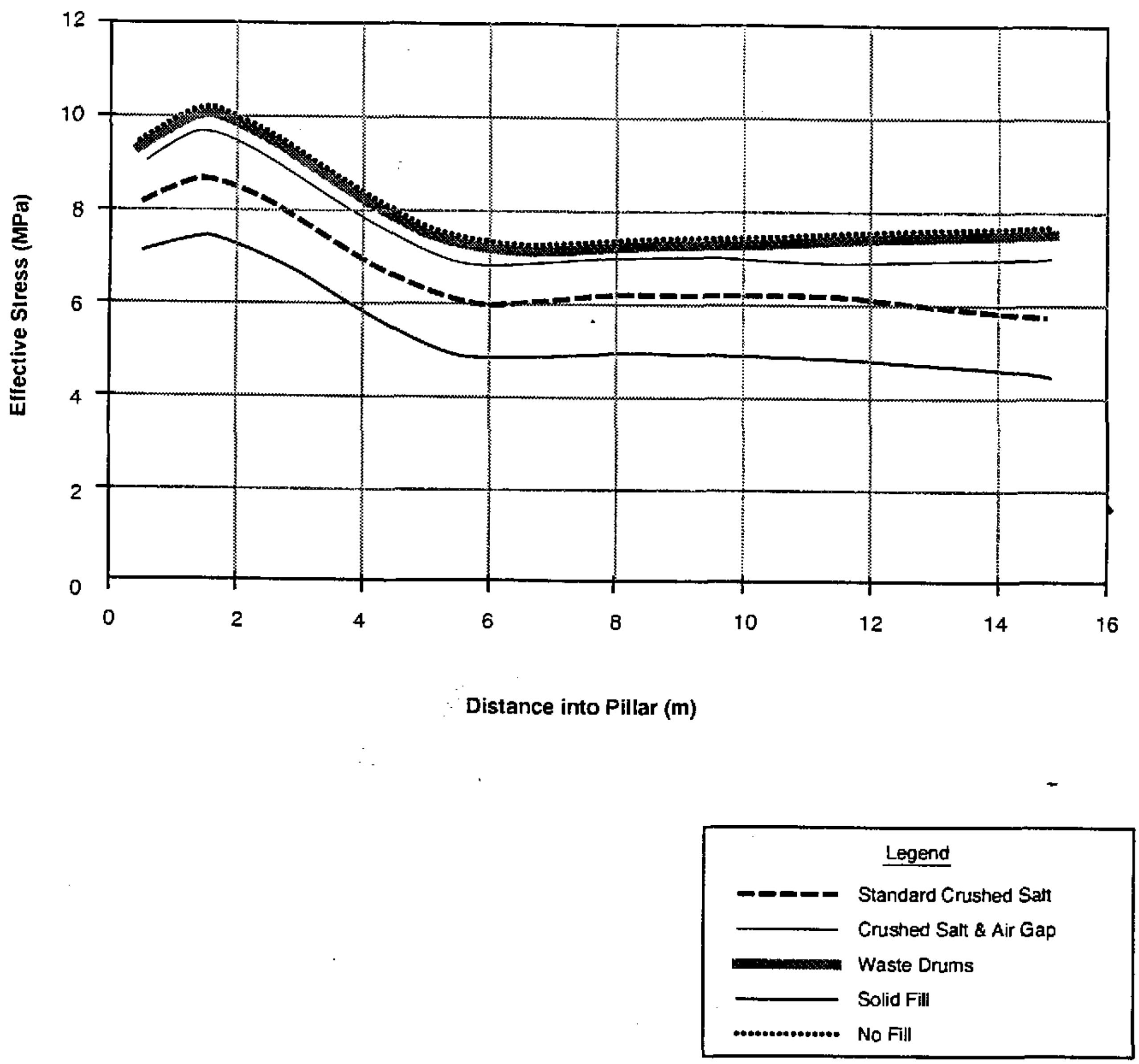


Figure 3-46
Effective Stress Through Pillar 10 Years After Excavation

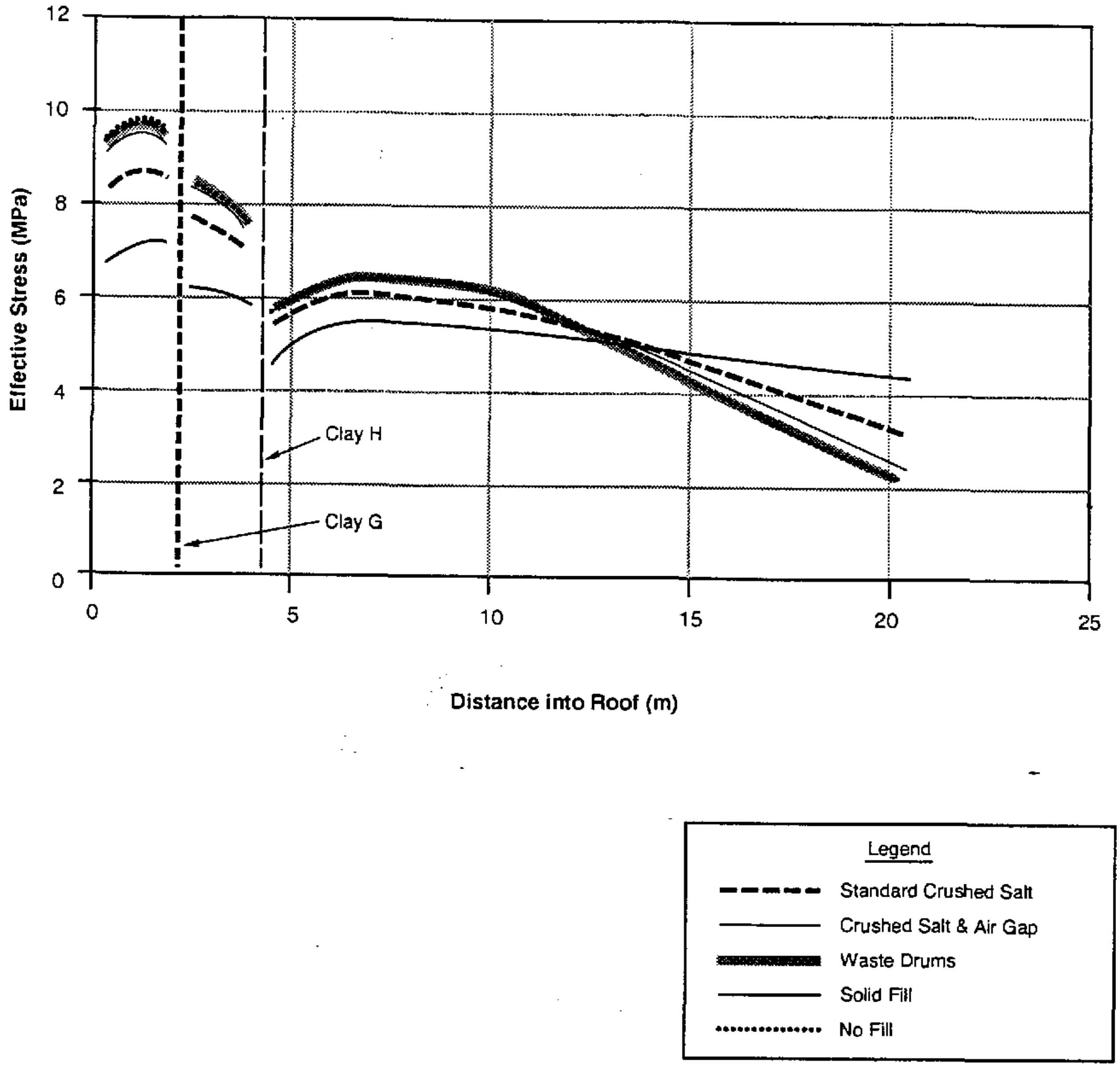


Figure 3-48
Effective Stress in Roof 10 Years After Excavation

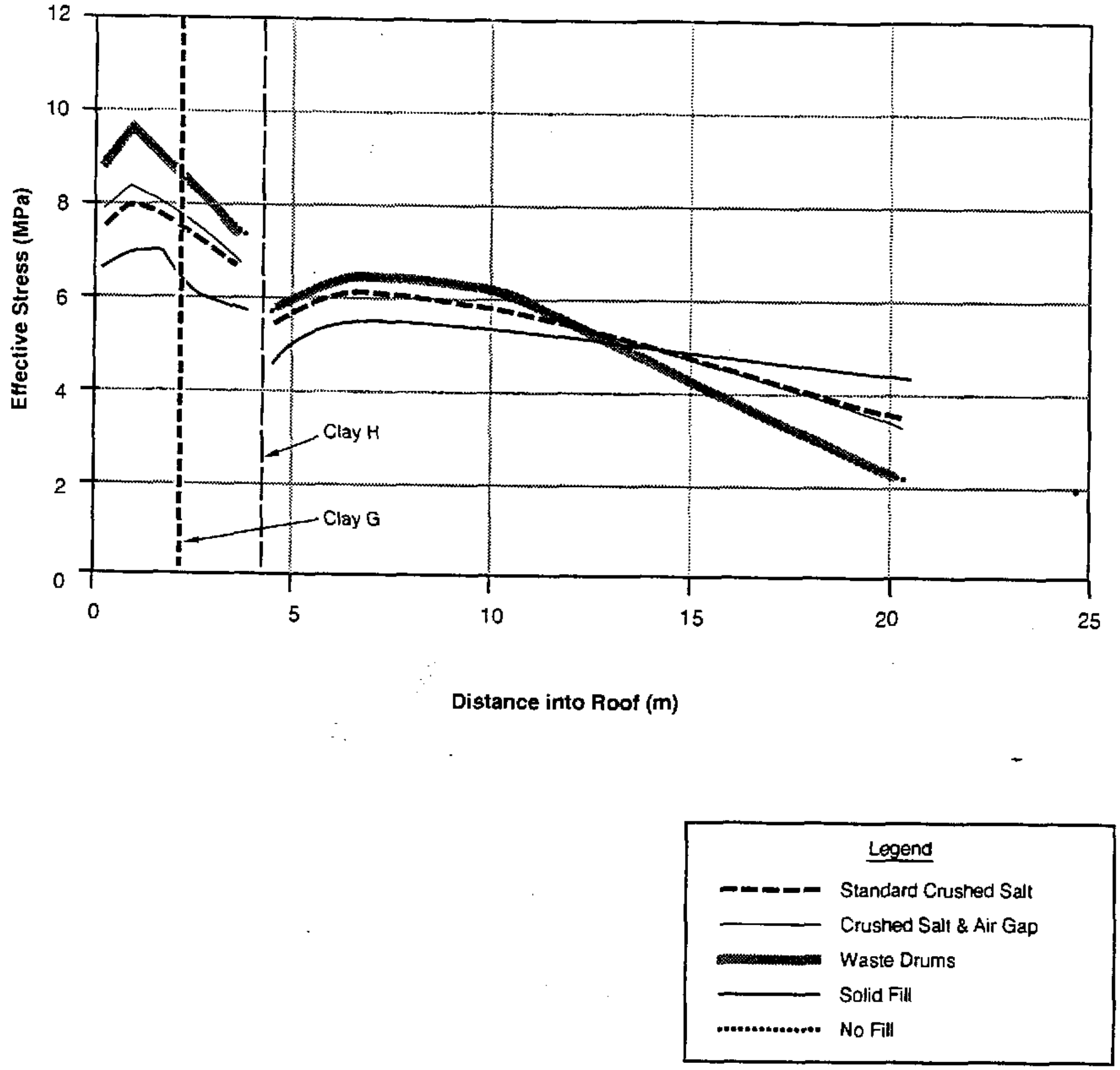


Figure 3-49
Effective Stress in Roof 20 Years After Excavation

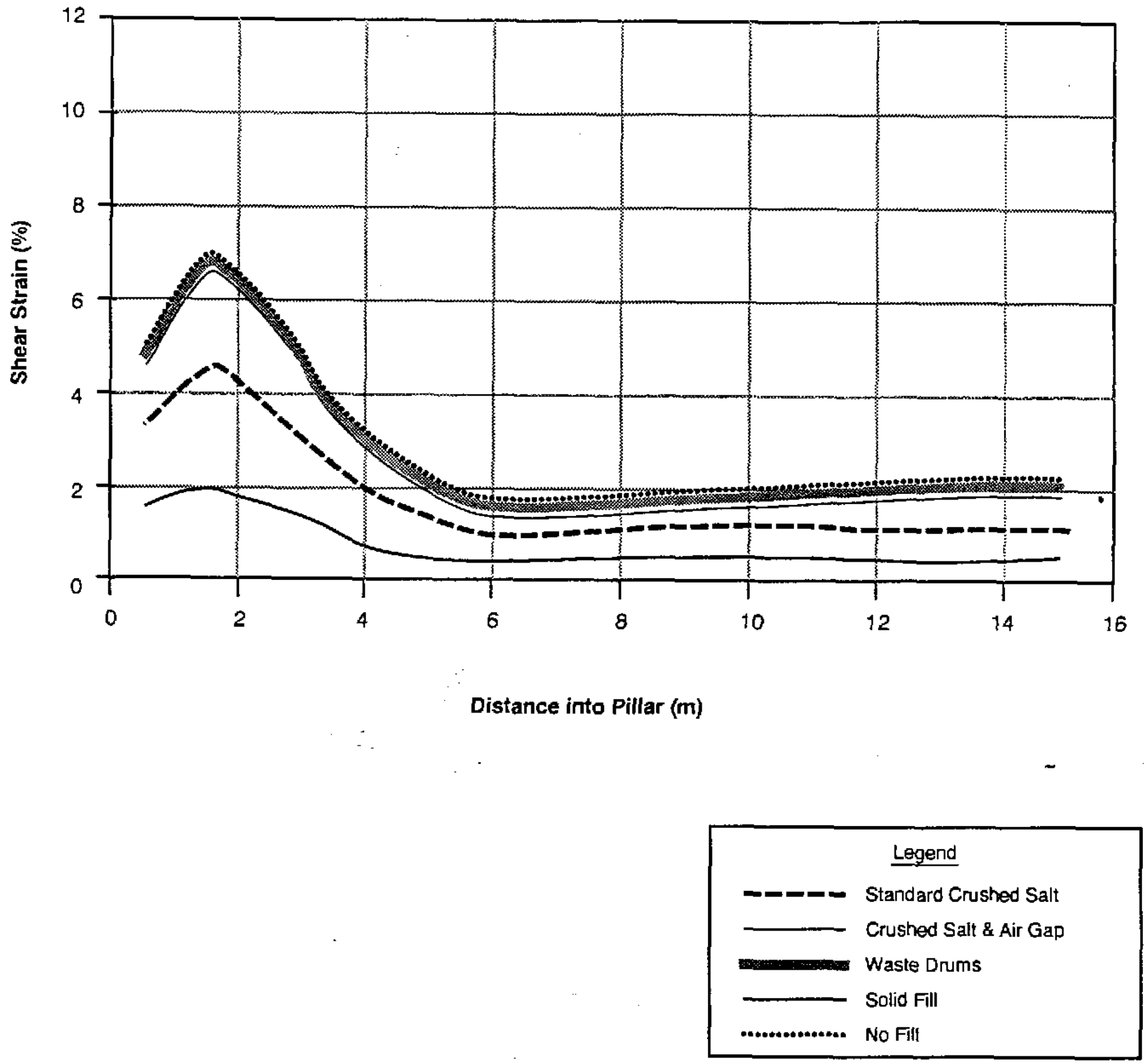


Figure 3-50
Total Shear Strain Through Pillar 10 Years After Excavation

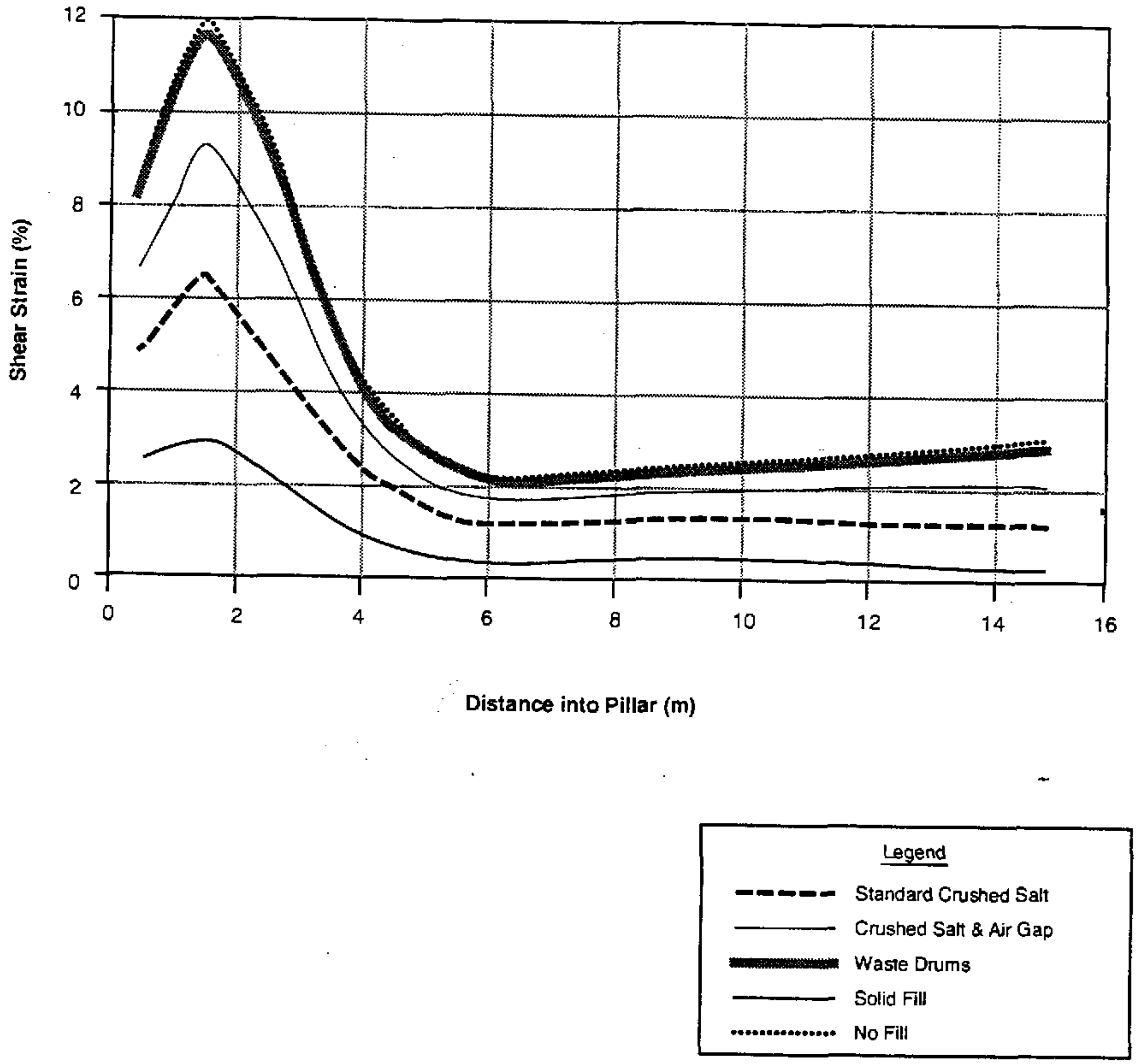


Figure 3-51
Total Shear Strain Through Pillar 20 Years After Excavation

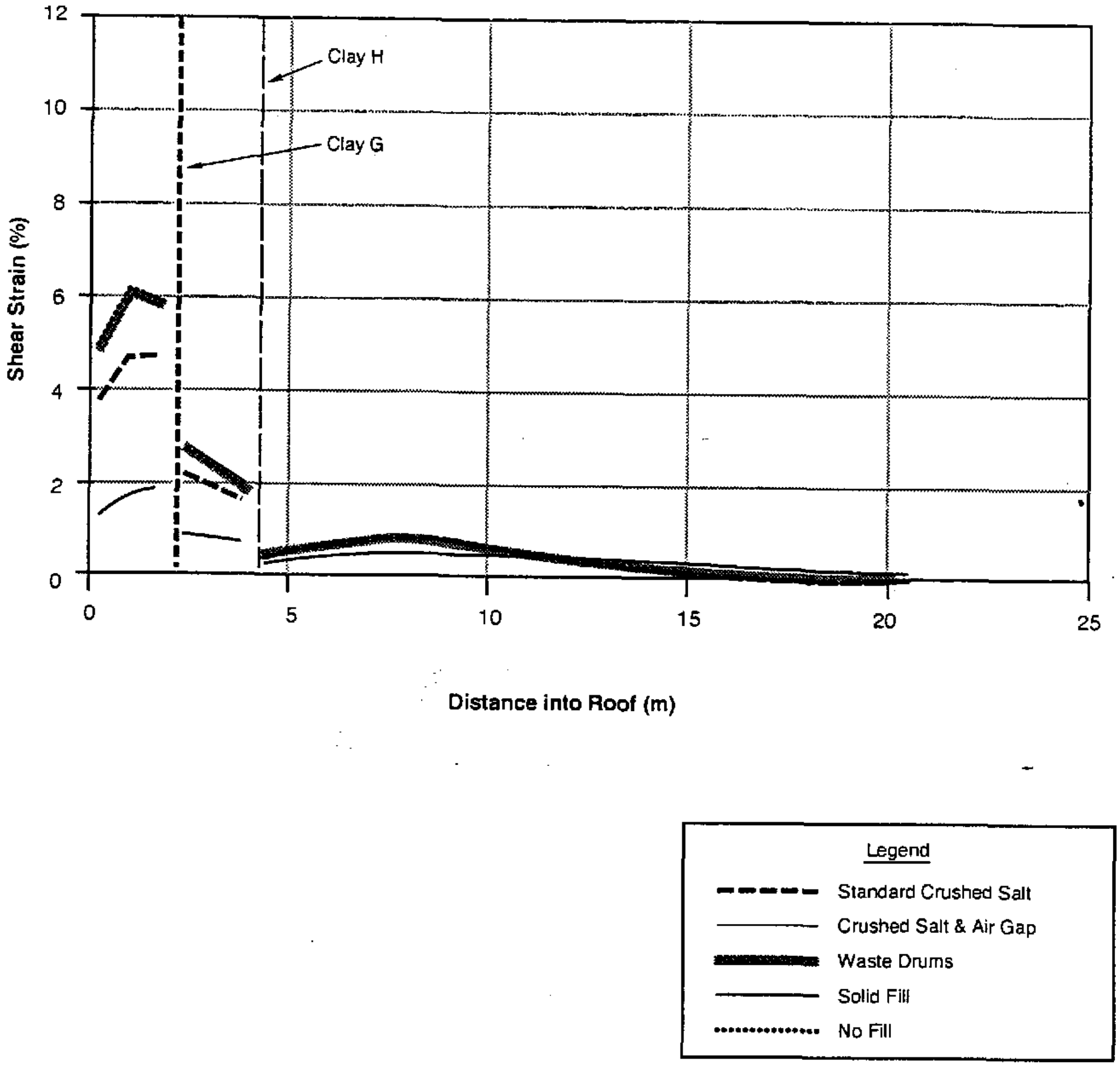


Figure 3-52
Shear Strain in Roof 10 Years After Excavation

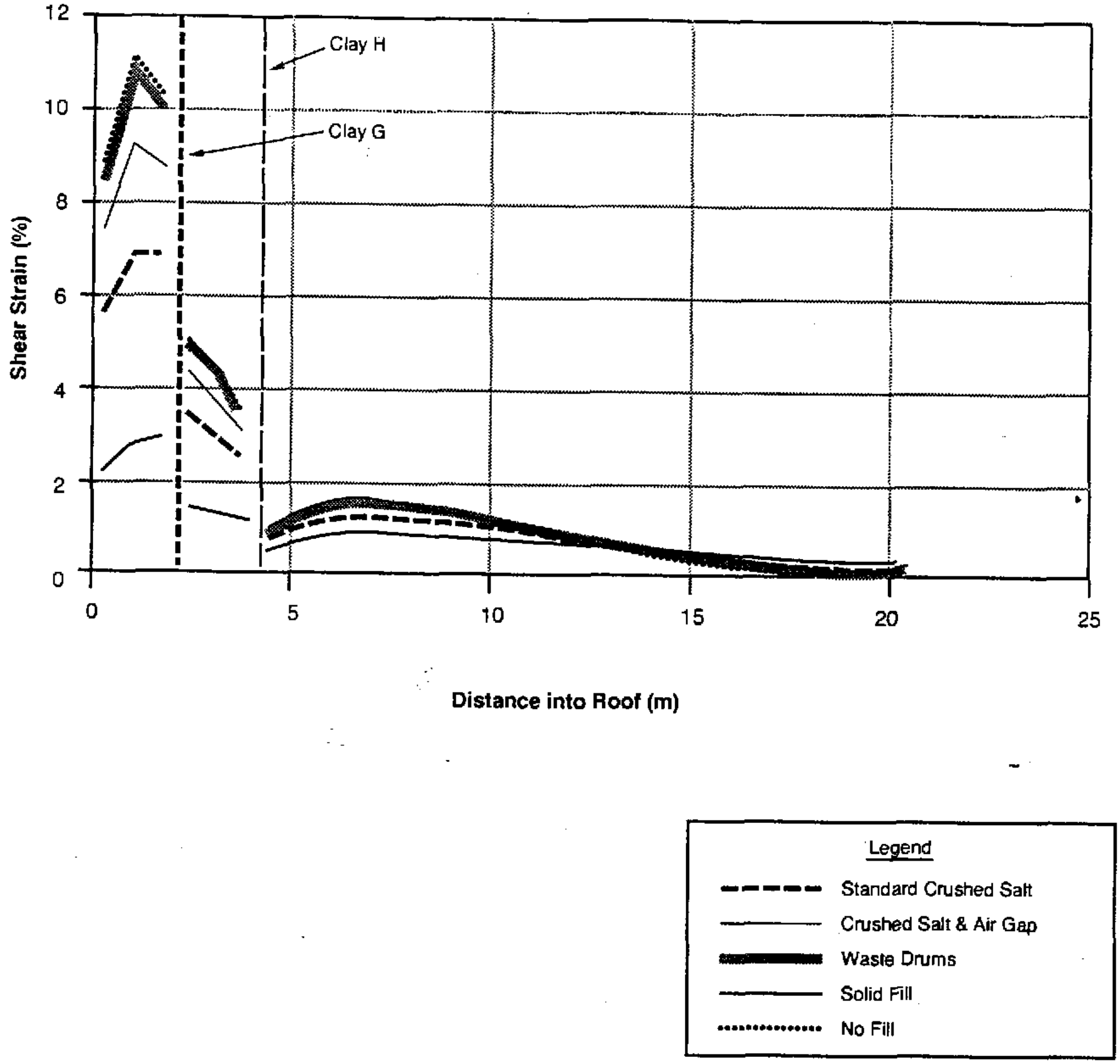


Figure 3-53
Shear Strain in Roof 20 Years After Excavation

4.0 Conclusions

This section presents conclusions as to whether placing backfill in the WIPP underground will provide a geomechanical advantage through increased room stability and decreased surface subsidence. The present analysis does not include influences/changes induced by oil or gas drilling and pumping, brine extraction or injection, potash or salt mining up to the WIPP boundaries, or groundwater table changes whether due to natural causes or due to pumping.

Throughout this report several prediction methods have been employed to assess the final subsidence above the repository. The methods are a representative sample of the available prediction techniques existing in literature: the mass conservation calculation, the NCB empirical method, the influence function method, and the numerical modeling approach (finite difference method). The consistency of the results for the different methods provides a high level of confidence about the accuracy of the outcome. Simple methods of subsidence prediction, such as the NCB, influence function, or mass conservation methods, appear to provide close agreement with the results of the numerical modeling.

The subsidence modeling results indicate that, to improve backfill performance, backfill must be placed early in the excavation phase, at the highest achievable density, and minimizing any void space, such as that between the backfill and the roof of the room. The requirement concerning the time at which backfill is emplaced is limited by the fact that some areas of the WIPP underground workings have been open for over ten years. Also, based on the FLAC modeling results, there appears to be little difference in total effect of backfill when different types and porosities of backfill are used, especially in the waste emplacement area, where the results are heavily dependent on the porosity of the waste. Based on the subsidence predictions, backfill emplacement does not significantly decrease the total subsidence in the waste emplacement area, because of the high porosity of the waste, the low stiffness of the waste, and the small amount of backfill relative to the waste volume. If the density or stiffness of the waste were increased prior to placement through waste treatment, such as compaction or solidification (cementation or vitrification), the expected subsidence in the waste emplacement area would decrease.

Subsidence at the depth of the Culebra Dolomite is expected to be similar to the predicted surface subsidence. The analysis of the FLAC model on horizontal strains at the Culebra Dolomite reveals low and uniform strains up to a maximum strain of 0.007 percent in experimental area and the shaft pillar area could reduce the surface subsidence in these areas, but the amount of surface subsidence, either with or without backfill, in these areas, is not considered to be significant.

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APPENDIX A
BACKFILL USES

A.1.0 Operational Uses for Backfill

A.1.1 Backfill for Fire Suppression.

One of the original uses for backfill in the waste emplacement area of the WIPP was to reduce fire hazard. The WIPP FEIS (DOE, 1980b) states that the CH-TRU waste rooms will be backfilled with salt to reduce potential fire hazards. The concern was that an external source could originate a fire (e.g., ignition of diesel fuel from handling machinery). The salt backfill would act as a barrier and limit the waste exposed to potential combustion. However, waste handling equipment design modifications have been made to reduce the probability of a diesel fuel fire (Westinghouse, 1986a). Subsequently, this accident scenario is no longer considered a credible event at the WIPP site (Westinghouse, 1986a).

Spontaneous ignition of a waste drum is an accident scenario that was cited in the Design Validation Final Report (DOE, 1986). Spontaneous ignition could occur within the contents of a CH-TRU waste container and can be readily propagated to adjacent drums. Backfill would encapsulate the drums and reduce the available oxygen for combustion. The issue of fire hazard has been evaluated by the Waste Drum Fire Propagation Task Force (Westinghouse, 1986a). Since the waste that will be emplaced in the WIPP must meet waste acceptance certification requirements (DOE, 1991c), which states that ignitable wastes are not acceptable at the WIPP (SNL/NM, 1991). The task force concluded that, although a sustained fire within a single drum may be credible, the overall probability that the fire will then propagate to adjacent containers is not a credible event, and therefore, salt backfill is not required for fire protection (DOE, 1986).

A.1.2 Backfill as a Cushion Above Waste Stacks

Backfill placed over the stacks of waste containers could function as a cushion if a portion of the waste emplacement room roof were to fail and fall. Roof falls have been observed in the SPDV rooms and in experimental rooms in the northern experimental area of the WIPP underground; roof falls in unsupported rooms are expected in the waste emplacement rooms. A layer of backfill, as included in the present waste emplacement design, could conceivably lessen the impact of a roof fall, decreasing the chances for a breach of the containers.

If a roof fall occurs after waste emplacement in a room and before the waste panel is filled and sealed, the cushioning effect could be advantageous. After the waste panel is sealed, there will be no adverse effect from a roof fall rupturing waste containers. It is anticipated that once waste emplacement begins, the total time between waste panel excavation and waste panel sealing will be less than five years. Experience with the SPDV rooms and experimental rooms indicates that roof falls in unsupported rooms are not likely to occur until at least seven years after excavation (DOE, 1992). Therefore, no advantage exists for backfill to be placed above the waste stack as a cushion if the excavation to sealing schedule is maintained.

A.1.3 Effect of Backfill on Retrievability of Waste

As stated in the FSAR (DOE, 1990a), the DOE committed to maintaining the waste emplaced at the WIPP during the initial test phase in a "ready retrievable" fashion. Backfilling over and around the waste stacks in the waste emplacement rooms during the test phase would have provided an additional physical barrier between the waste and WIPP personnel while the test phase was being monitored. Concern also existed as to whether the backfill would reconsolidate during the test phase and make retrieval of the waste containers more difficult. Due to the recent modifications to the test phase test plans (Arthur, 1993), ready retrievability of waste following the test phase is no longer an issue, and the test phase location has been changed to a site other than the WIPP underground. Once the decision is made to license WIPP as permanent waste repository, the waste should not be required to be ready retrievable, and the retrievability issues mentioned above will no longer be valid.

A.2.0 Long-Term Performance Uses for Backfill

Potential uses for backfill designed to enhance the long-term performance of the WIPP are briefly described below. In-depth investigation of these potential backfill uses is beyond the scope of this report, however, brief descriptions are provided here to inform the reader of other potential uses for backfill materials in the WIPP underground.

A.2.1 Backfill as an Engineered Barrier or Seal Material

Panel seals and shaft seals are the primary engineered barriers designed for the isolation of the waste from the accessible environment at the WIPP. Placement of backfill in the main entries of the waste emplacement area and in the access drifts located between the shafts and the waste emplacement area has been proposed to enhance the isolation performance of the WIPP repository. Crushed salt backfill could be placed at the time of repository decommissioning. The backfill would be reconsolidated by the forces exerted on it by the walls, floor, and roof of the excavated drifts as the intact salt creeps in. The reconsolidation would reduce the porosity and permeability of the backfill (Sjaardema and Krieg, 1987).

The need for backfill as an engineered barrier and its design requirements would need to be determined through the performance assessment modeling being performed by SNL/NM (SNL/NM, 1991).

A.2.2 The Interaction of Backfill and Gas Generation.

Analyses of the long-term performance of the WIPP disposal system performed by SNL/NM have identified a potential problem related to gas generation. Lappin et al. (1989) discusses the possibility that up to 1,500 moles of gas (mostly hydrogen, carbon dioxide, and methane) can be generated per drum of waste from anoxic corrosion, microbial degradation, and radiolysis at rates that may be as high as 2.55 moles/drum/year. Anoxic corrosion of iron, steel, and aluminum alloys present in the waste and waste containers may generate large quantities of hydrogen gas if sufficient brine is available. The following anoxic reaction requires and consumes brine:

METAL + BRINE $\rightarrow$ METAL OXIDES + HYDROGEN GAS

Although processes exist to dissipate excess gas pressure, these processes are currently believed to be slow relative to the current estimates of generation rates, resulting in gas pressures that may temporarily exceed lithostatic pressure. Recent estimates of potential brine inflow (Deal and Bills, 1994; Deal et al., 1994) are much lower than those assumed by Lappin et al. (1989), and there may not be enough brine inflow to produce large quantities of hydrogen gas.

One approach to alleviate the problem of gas exceeding lithostatic pressure was suggested by Brush (1990) and involves the use of gas-getters as backfill additives. Gas-getters are compounds that chemically react with generated gases (most effectively with carbon dioxide) to produce a solid product, thus removing some of the gas from the room environment. Any decision to incorporate gas getters as a backfill additive will need to be based on the resolution of several current issues, including:

- A quantification of the amount of brine that might reasonably be expected to enter a waste emplacement room after sealing and closure
- A quantification of the total amount of each gas that might be produced and the generation rates of those gases

- A quantitative assessment of the ability of the Salado Formation to dissipate excess gas pressure

- A determination of the effectiveness of proposed backfill additives in removing the required amounts of gas.

A full study of the process of brine inflow and gas generation at the WIPP is being investigated by DOE.

A.2.3 Effect of Backfill on Radionuclide Sorption

Bentonite has been proposed as a backfill additive to promote adsorption of radionuclides within the waste storage rooms. Bentonite is commonly used to adsorb contaminants dissolved in dilute groundwaters. However, in high-magnesium brines, significant uncertainties exist regarding the effective ability of bentonite to adsorb radionuclides. The effectiveness of radionuclide sorbers as backfill additives is being evaluated by an SNL/NM experimental program (DOE, 1989).

A.2.4 Effect of Backfill on Brine Absorption

The addition of bentonite to a crushed salt backfill has been proposed to absorb some or all of the brine that may flow into the storage rooms. This approach attempts to minimize the volume of contaminated brine that may be available to migrate away from the repository by natural processes or in response to human intrusion scenarios. Due to the unknowns associated with the reaction of WIPP brine with bentonite, additional study may be necessary.

A.2.5 Backfill Material to Reduce the Disturbed Rock Zone Around Seal Locations

An excavation of underground openings at the repository horizon disturbs the state of stress around those openings. This stress disturbance induces creep closure, resulting in the formation of a DRZ surrounding the excavation. The extent of the DRZ is defined by the boundary where the hydraulic properties of the salt are changed from their undisturbed values. This is physically manifested by the formation of fractures and other deformation of the host rock, resulting in a localized increase in permeability around the excavations (Beauheim et al., 1991; Stormont et al., 1991).

This locally increased permeability also increases in the potential for brine flow into or out of the repository. Additionally, the development of an extensive DRZ may provide a route for brine to circumvent the panel entry seals. This may be a short-lived problem, since as creep continues, the DRZ will begin to reduce in size, as the fractured halite within the DRZ begins to reconsolidate under lithostatic pressure (Cook and Case, 1991). The concern is that the anhydrite beds, which are located close to the repository horizon (e.g., Marker Bed 139 located a few feet under the excavation), are not self-healing and that any fractures due to DRZ development will not fully close during reconsolidation.

In order for the creep to begin to reduce the size of the DRZ, there must be some resistance to creep provided by the contents of the room. In order to reduce the expansion of the DRZ and to facilitate the reconsolidation of the halite within the DRZ, it may be desirable to emplace a backfill material, such as crushed salt, which would reduce the amount of excavation closure. The actual extent of the DRZ will then be dependent on the length of time that the drift has remained open without backfill material and the initial emplacement density of the crushed salt backfill material.

This use of crushed salt backfill material is primarily applicable to the proposed locations of panel entry seals and the waste emplacement area main entry seals. Any use of crushed salt material in these locations would be in conjunction with the design and construction of the entry seals. The design and performance analysis of entry seals is being performed by SNL/NM (Argüello and Torres, 1987; Argüello, 1988, Hansen, et al., 1993).

A.2.6 Backfill Additives as Intrusion Markers

Markers are structures, including buried structures, designed to indicate the existence of the WIPP site and the dangers associated with drilling or mining into the site. These markers can be structures that are messages in themselves or structures that provide graphic or written messages. These markers can also be structures designed to introduce anomalies in the gravimetric, seismic, electrical conductivity, and magnetic profiles of the site. Subsurface markers at the depth of the waste have been proposed by an expert panel (Trauth et al., 1992). Such markers would have to be placed above the waste drums, possibly as part of a backfill material. Markers that were suggested by the expert panel to be placed at the waste depth include ultrahard material fragments or Thermit[1] ignited by a mechanism set off by drilling through an enclosing titanium container.

[1]Thermit is a mixture of aluminum powder and iron oxide used in welding that, when ignited, generates a great amount of heat.