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Concepts for Operational Period Panel Seal Design at the Waste Isolation Pilot Plant

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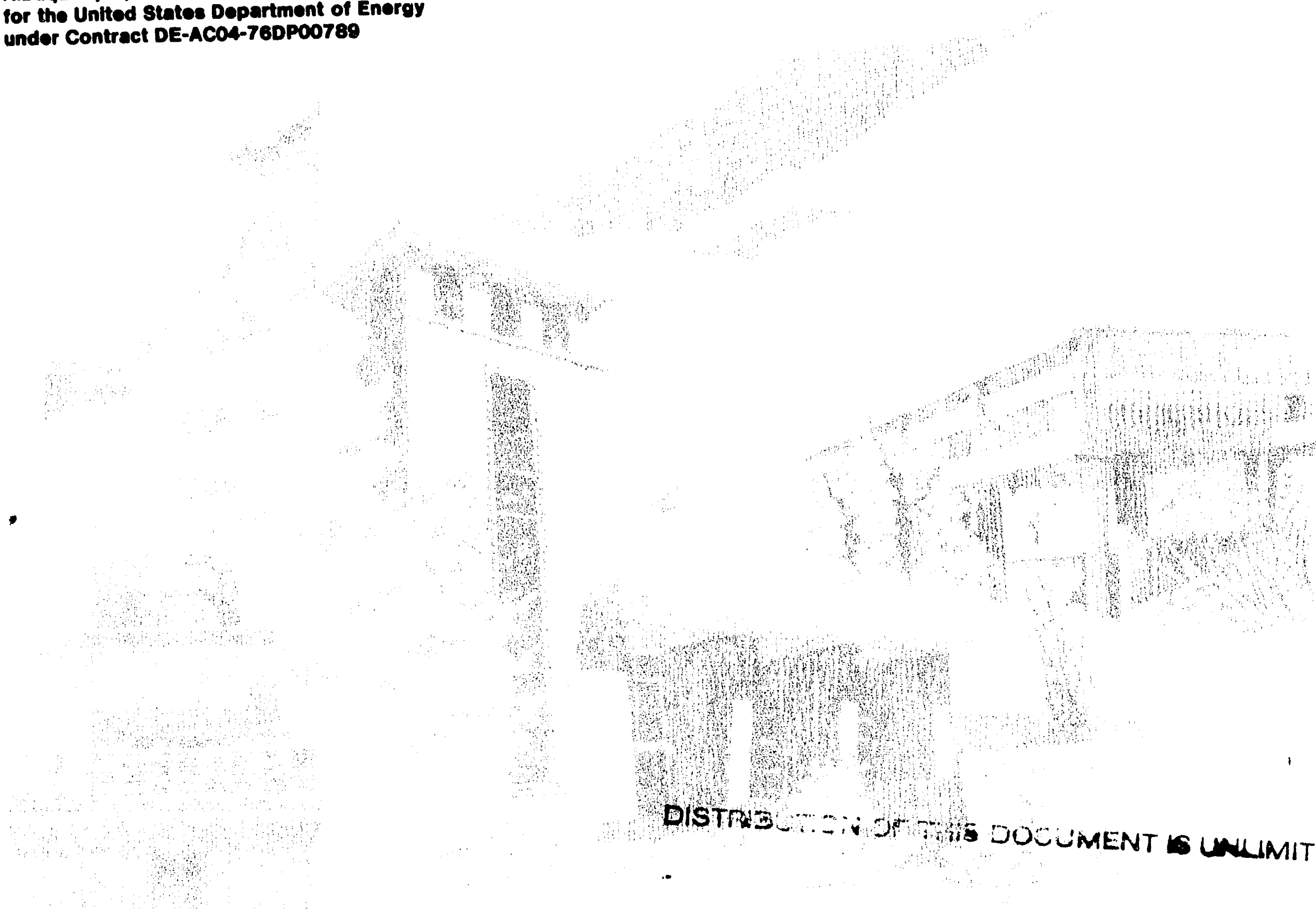

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ABSTRACT

Concepts for underground panel or drift seals at the Waste Isolation Pilot Plant are developed to satisfy sealing requirements of the operational period. The concepts are divided into two groups. In the "NOW" group, design concepts are considered in which a sleeve structure is installed in the panel access immediately after excavation and before waste is emplaced. In the "LATER" group, no special measures are taken during excavation or before waste emplacement; the seal is installed at a later date, perhaps up to 35 years after the drift is excavated. Three concepts are presented in both the NOW and LATER groups. A rigid sleeve, a yielding sleeve, and steel rings with inflatable tubes are proposed as NOW concepts. One steel ring concept and two concrete monoliths are proposed for seals emplaced in older drifts. Advantages and disadvantages are listed for each concept. Based on the available information, it appears most feasible to recommend a LATER concept using a concrete monolith as a preferred seal for the operational period. Each concept includes the potential of remedial grout and/or construction of a chamber that could be used for monitoring leakage from a closed panel during the operational period. Supporting in situ demonstrations of elements of the concepts are recommended.

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1.0 INTRODUCTION

The Waste Isolation Pilot Plant (WIPP) near Carlsbad, New Mexico is planned as a mined geologic repository for transuranic wastes generated by defense programs of the United States Department of Energy. Sealing systems in WIPP panels, drifts, shafts, and boreholes are important components of the facility that will be designed to limit the release of waste materials to the accessible environment by preventing repository accesses from becoming preferred pathways. An ongoing evaluation will attempt to establish whether there should be both postclosure and operational requirements for the panel and drift seals. The present study was initiated to assess potential simplifications in design, construction, and monitoring that might result if the panel and drift seals have no postclosure performance requirements. Previous design studies (Van Sambeek et al., 1993a) have developed design concepts assuming both operational and postclosure requirements are applicable to panel and drift seals.

This document presents alternative design concepts for the WIPP panel and drift seals considering only the requirements of the operational period. The operational period is assumed to be 35 years: 30 years for salt excavation and waste emplacement and 5 years for room backfilling and underground decommissioning. Discussion centers on the panel seals, particularly, because eight panels are planned and only one panel has been excavated to date. The concept developed for a panel might be the same for a drift. The design concepts are evaluated and their advantages and disadvantages are compiled. Actual design of panel and drift seals for the operational period will make use of analyses and technical tradeoffs developed in this report. Materials proposed for use in the seals are selected to be compatible with the surrounding host rock and, to the extent possible, readily available. Alternative emplacement procedures are considered to reduce construction time and cost, to provide for safety during installation, and to produce an effective seal as early as possible.

The seal functional requirements and performance criteria for the operational-phase panel sealing subsystem are summarized in Table 2-1. For purposes of this study, no long-term requirements for the panel seals are considered. This allows evaluation of possible seal concepts for operational period requirements alone, which involve restrictions established by the Environmental Protection Agency (EPA) under the Resource Conservation and Recovery Act. The principal operational function of the seal is to limit gas leakage from the waste side of the panel to the main access drifts during repository operation. The criteria for gas leakage assume the panel to contain volatile organic compounds that are characteristic of mixed waste.

Concepts developed here establish several seal alternatives that can be integrated into the large-scale seal tests for verification. It is expected that final design of drift and panel seals will benefit from the results of underground experimentation and demonstrations. In addition to several concepts for panel seals, the recommendations for underground tests are a vital part of this report. The iterative design philosophy used in this report first establishes the concepts, then evaluates (through full-scale demonstration) certain of the key elements, and then is followed by complete detailed design.

1.1 Purpose of the Concepts Study

Parsons Brinckerhoff Quade and Douglas (PBQ&D) recently completed a study of seal design alternatives for sealing panels, drifts, shafts, and boreholes (Van Sambeek et al., 1993a). All of the seal alternatives had functional requirements for the operational period (35 years), the short term (100 years), and the long term (10,000 years). In contrast, the present report examines possible panel seal concepts that impose only operational period requirements.

A firm decision as to whether the seals for the eight waste panels (16 seals) have requirements for both the operational period and the postclosure period is pending. If it is decided that the panel seals have no functional requirement for the postclosure period, they will be designed to operational-period requirements only. Cost savings may be significant if the operational seals do not have to be as substantial (multiple components) as the postclosure seals or do not have to meet postclosure requirements. The operational seals will be designed to limit release of gases from filled disposal panels during the operational period of approximately 35 years. Sealing during the operational period assumes that there is access to the external face of the seal for remedial maintenance, ventilation, and monitoring.

Only panel seal design concepts are explored in this study. In particular, six alternative concepts are developed: three each for "NOW" and "LATER" strategies. The NOW concepts examine advantages and disadvantages of initiating seal activities immediately after excavation and before waste emplacement, and the LATER concepts deal with the issues of sealing at a later date after waste emplacement. The six alternative concepts are examined for advantages, disadvantages, and initial capital costs.

1.2 Report Organization

Section 2.0 more thoroughly develops the design basis, assumptions, and design goals for this study. The six alternative concepts, three each for NOW seals and LATER seals, are presented and described in Section 3.0. The rock mechanics issues relevant to this study are described in Section 4.0. The rock mechanics issues include: (1) an overview, (2) pertinent rock properties, (3) an analysis of the rigid sleeve concept, development of a disturbed rock zone (DRZ) around openings of three shapes, and the loading imposed on the sleeve, and (4) analysis of the effectiveness of back pressures from a yielding sleeve on the healing of the DRZ and control of interbed deformation around the sleeve. An initial capital-cost estimate is made in Section 5.0. Advantages and disadvantages of these concepts are listed in Section 6.0. Section 7.0 discusses both the NOW and LATER seal concepts and emphasizes favorable design attributes. Finally, in Section 8.0, recommendations are made for full-scale seal demonstrations that would provide design data and would be used to help validate concepts for the panel seal system. Section 9.0 is a list of references.

2.0 DESIGN BASIS AND ASSUMPTIONS

2.1 Design Basis

A project design basis document was established from the preliminary design requirements document (DRD) (Bailey et al., 1992a) and the preliminary data base document (DBD) (Bailey et al., 1992b). A design basis document is a requirement of the internal PBQ&D Quality Assurance Program, which is described in other reports (Lin and Van Sambeek, 1992). The design basis is an instrument of control of any design and in this case is used even at the conceptual stages. It contains the design criteria, design methodology, and applicable codes and standards as well as site- and project-specific data and requirements specified by Sandia National Laboratories. For rock mechanics, additional design bases are cited in the relevant sections of this report.

2.2 Assumptions

Because of the lack of design information on some aspects, the following assumptions are made for purposes of this study:

a. The design life of the operational period panel seal is 35 years: 30 years for the waste emplacement period and 5 years for the underground decommissioning period (Bailey et al., 1992a).

b. The length of the operational period seal is 16 ft (4.8 m), which roughly equals one diameter of excavation. In this exercise, the length of the seal was varied (one diameter and less) to assess liner loading and stress concentrations. The overall loading on a plug approximately one diameter in length was considered practical and constructible, yet the seal is not excessively long. The calculations supporting this assumption will be discussed in more detail in Section 4.3.

c. The gas pressure generated in the waste panel will increase gradually from zero at the time of seal installation to 10 psid (70 kPad) during the seal's service life. Gas build-up will be slow enough that it will not affect healing of the DRZ in salt surrounding the seal.

d. A membrane material acceptable for use in the WIPP underground will be available for use as a gas-tight barrier. Materials considered in the concepts are assumed to be available or obtainable as well as acceptable in the WIPP underground.

e. Lightweight foam concrete with perlite, vermiculite, or polystyrene pellets can be used as the rigid-plastic material for the yielding sleeve. Otherwise, a proven rigid-plastic metallic honeycomb is available, but at significant cost.

f. The adequacy of the operational seal design can be assured by multiphased installation of the seal so that continuous monitoring and operational remedies as required can be made:

- If the leakage exceeds the allowable rate, remedial grouting will be performed as required.
- If the gas pressure inside the waste panel indicates that the 10 psid (70 kPad) design pressure will be exceeded, engineering measures, such as a cast-in-place concrete monolith, can be installed to reinforce the steel plate bulkhead. Very conservative predictions of gas pressure indicate that spontaneous detonation or instantaneous inundation and corrosion could produce higher pressures (as high as 150 psi [1 MPa]).
- If remedial grout is not effective, a second seal that isolates a monitoring room may be installed. The gas leaking from the waste panel could be monitored and hazardous material treated appropriately.

g. This study considered the use of existing WIPP mining equipment. However, if required, custom-made equipment can be provided for construction.

h. The stratigraphy shown in the preliminary data base document (Bailey et al., 1992b) is assumed to be typical for the entire repository horizon.

i. The salt DRZ will develop and heal as a function of the state of stress, whereas the DRZ in Marker Bed 139 (MB139) will not reheal. Because the DRZ enhances permeability, reduction of its development and the possibility of remediation by grouting are important for design concepts.

2.3 Design Goals

The focus of this report is to generate seal design concepts that meet specific goals. The regulatory requirements pertaining to these goals for the operational period are listed in Table 2-1. These include limiting gas flow out of a disposal room, providing a sound structure, and mitigating the development of the DRZ. Each requirement has attendant concerns specific to the setting at the WIPP. For example, a goal of the design concept might be to allow for the potential monitoring of gases or to allow access for remedial measures if needed. The seals also must be designed to function within the constraints of the geological stratigraphy. Potential leakage through the stratigraphy, and therefore the idea of prevention of DRZ development, is central to this study.

A key to understanding the scope of this report is to have a familiarity with the DRZ and its implication to the sealing of a waste panel. When an opening is created at the WIPP Site, the rock instantaneously moves into the excavated space, as is typical of any underground opening. At WIPP, because it is situated in an evaporate sequence of rock, the deformation continues as a function of time. The deformation within the rock can create void space, often referred to as damage or dilation, which may be particularly detrimental in the brittle interbeds. Because the damage increases with time and other aspects of the excavation, such as size and geometry, a significant advantage in leak prevention might be achieved if a sleeve could be emplaced before the damage zone becomes too large or well developed. In other words, doing something NOW to minimize the DRZ is considered, rather than waiting several years and then sealing the panel.

Table 2-1. Panel Sealing Subsystem (Operational Phase)

Functional Requirements	Performance Criteria	Constraints/Assumptions
1. Limit release of waste in gaseous medium from filled waste disposal rooms during operational phase.	1. Limit gas escape flow rate to 7 x 10^{-3} cubic feet per minute (3 x 10^{-6} cubic meter per second).	A. It is assumed that 16 panel seals will be required. B. Panel seals will not obstruct or interfere with mine operations.
SEAL STRUCTURE		
1. Provide structural integrity	1. Withstand calculated loads from gas pressure, rock closure in, the short-term, lithostatic pressure. A minimum factor of safety of 1.5 to be applied to calculated design loads.	C. The option to do maintenance grouting will remain until access to the seals is precluded. D. It is assumed that the age of the panel entry will be approximately 5 to 30 years when seals are emplaced.
2. Provide resistance to gas flow.	2. Provide permeability of less than 6 x 10^{-6} darcy. (6 x 10^{-18} meters squared).	E. It is assumed maintenance of openings will retain existing dimensions 14 or 20 ft (4.3 or 6.1 m) wide by 12 ft (3.7 m) high.
DRZ SEALING		
1. Provide resistance to gas flow. liquid flow.	1. Provide permeability of less than 6 x 10^{-6} darcy (6 x 10^{-18} meters squared) in the DRZ and the interface between the seal structure and the host rock.	F. Concrete and grout formulations will conform to the design basis document.
		G. Grouting pressures will be controlled to prevent hydro-facturing. H. A minimum equipment envelope of 12 ft wide x 12 ft high (3.7 m x 3.7 m) must be maintained if seal structure is emplaced before waste emplacement is initiated in disposal rooms.

Modified From Bailey et al., 1992a

This study also evaluates the DRZ and other aspects of the seal if it is constructed after waste is emplaced. In other words, the seal is constructed LATER. The seal would provide separation of the waste from the workers for the remaining operating life of the WIPP and would have to meet the same functional requirements whether it is emplaced NOW or LATER. In addition, fourteen potential seal locations already exist in the WIPP underground. Therefore, this study must devise concepts for the LATER case at a minimum. If significant advantage in leak prevention can be shown, then one of the NOW concepts may be warranted on a technical or fiscal basis.

3.0 CONCEPTS FOR OPERATIONAL PERIOD PANEL SEAL DESIGN

Two basic concepts of operational seal design were studied for this report. They are referred to as the NOW concept and the LATER concept. The NOW concept involves installing a structural sleeve at a future seal location immediately after excavation and completing the seal after waste emplacement. Early sleeve emplacement will effectively arrest continued development of the DRZ. In the LATER concept nothing is done at the excavated seal location until the storage area is ready for sealing after waste emplacement in the panel. Comparing the two concepts illustrates the influence of creep deformation and DRZ development and the mitigating effects that can be achieved by emplacing a sleeve structure as soon as possible after excavation.

A few key design requirements led to the concepts chosen. For example, any considerations for the NOW concepts must maintain access for delivery of the waste to the panel. Therefore, sleeve concepts are developed to control the DRZ immediately, and the seal is completed after waste emplacement. Variations on the sleeve concept examined here include a rigid sleeve to resist the entire lithostatic load, contrasted with a more flexible sleeve (yielding) that provides a nominal backstress on the perimeter of the opening. A comparison is made in the NOW concept between a circular-shaped and a horseshoe-shaped drift. The LATER concepts do not need to provide access through the seal structure for waste-handling and emplacement, so monolithic structures can be considered and two monolith-type concepts are developed. To contrast with the monoliths in a LATER concept, a simple and initially inexpensive steel ring is proposed as another concept. Each concept can be augmented to include a monitoring chamber.

Figure 3-1 shows three concepts of the NOW panel seal in which a sleeve is installed immediately after excavation to control the DRZ in the salt and reduce deformation of MB139 underlying the seal. After waste emplacement in the panel, a stiffened steel-plate bulkhead will be installed at the waste side to complete the operational period seal. Both rigid and yielding (deformable) sleeves are considered. The concepts considered are a cylindrical rigid sleeve built of precast members, a horseshoe-shaped yielding sleeve, and a cylindrical steel ring surrounded by inflated tubes to act as another form of yielding sleeve. The effectiveness of the panel seals can be monitored during the operational period, and remedial grouting can be provided as required.

Three concepts for LATER seals are shown in Figure 3-2. The LATER seals require no action until the time of panel closure. By the time of panel closure, a significant DRZ is expected to have developed around the opening, which might have required rock bolts or other ground support for operational safety. Significant deformation of the unrestrained floor uplift could have taken place, fracturing MB139. Concepts 4 and 5 show two bulkheads that could be used to form a monitoring chamber. A monitoring chamber for use during the operational period could be added to any of the concepts. Concept 6 is a single concrete monolith that is installed after excavation of the DRZ in salt and MB139.

For a seal using two bulkheads, as illustrated in Concepts 4 and 5, a monitoring chamber can be formed between the bulkheads and used for leakage detection or gas collection. A leakage collection system could be built at the center of the chamber for monitoring leakage through MB139 or the clay seams. The drift-side bulkheads, as illustrated in Figure 3-2, are equipped with inflated tubes to assure a reasonably airtight seal immediately after

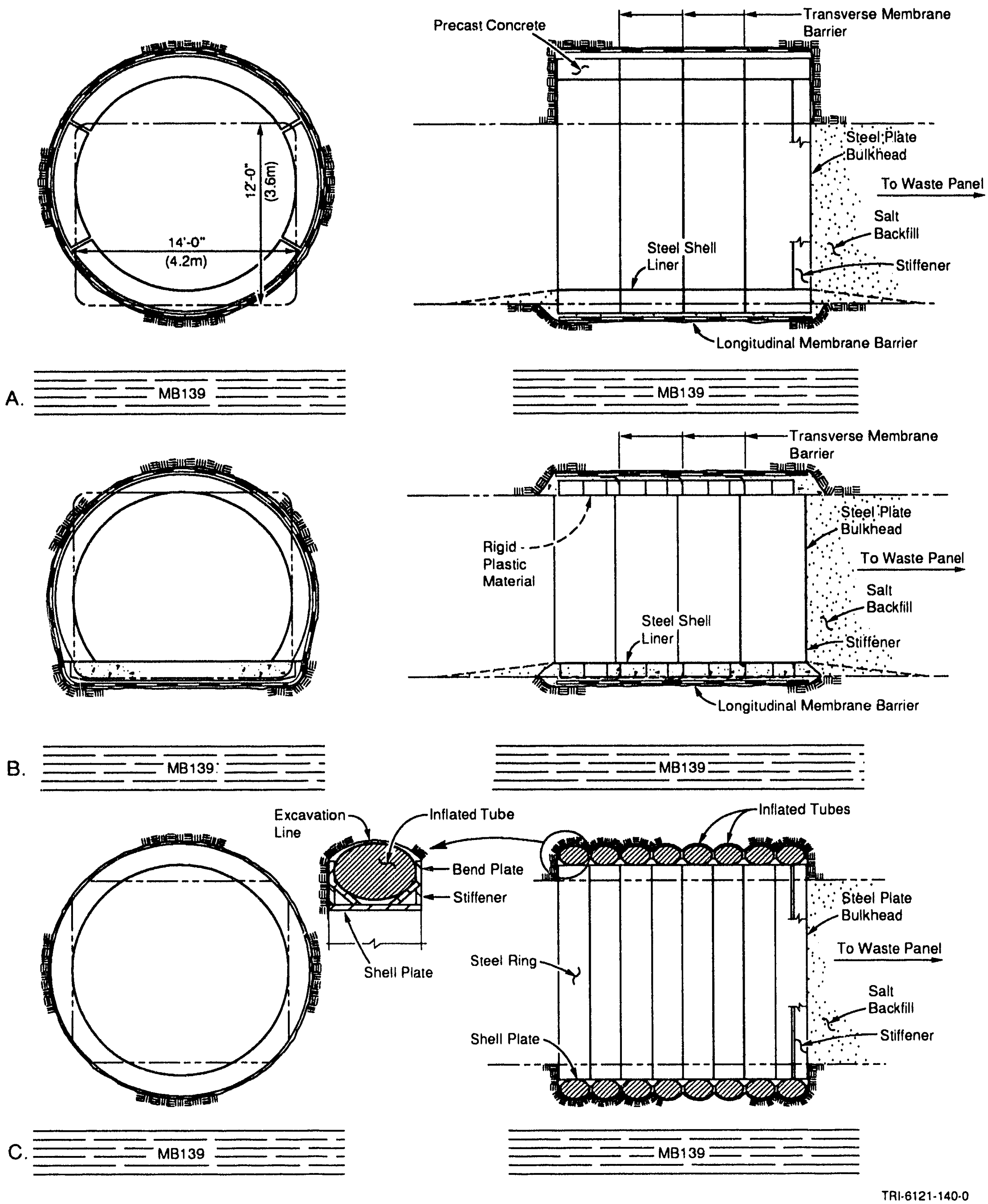


Figure 3-1. NOW concepts for operational period seal.

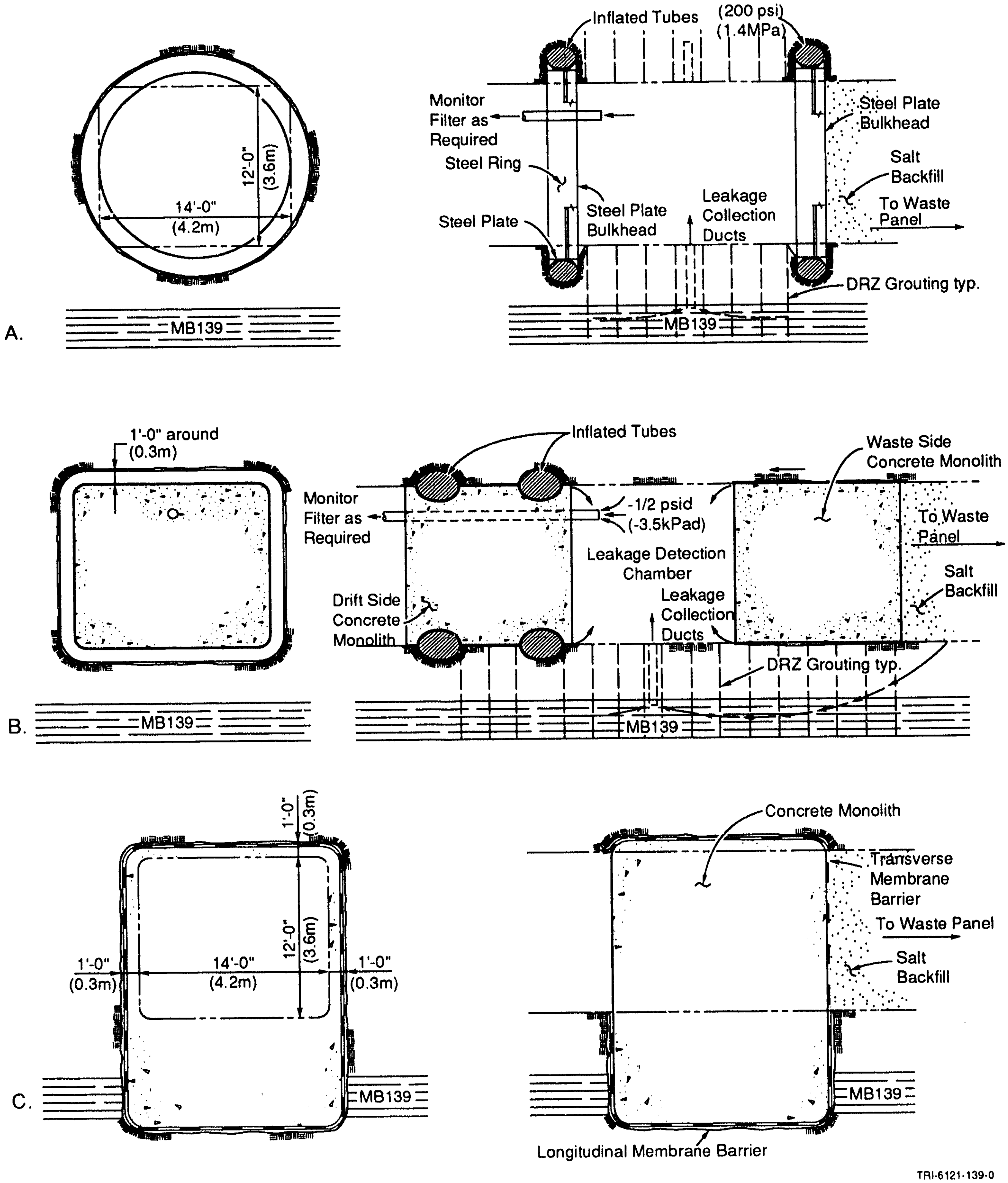


Figure 3-2. LATER concepts for operational period seal.

installation. The back pressure from the inflated tube might also expedite healing of the DRZ in salt around the seal. The leakage-detection chamber could function by application of a negative pressure during the operational period. The air inside the chamber could be monitored for volatile organic compounds (VOCs), which would indicate that some of the waste drums had been breached inside the waste panel and indicate leak passages through the waste-side bulkhead, the salt DRZ, or MB139. The exhaust from the leak-detection chamber could be filtered as required, to remove any hazardous material before venting to the atmosphere. Constructing the second bulkhead to form the leakage-detection chamber could be postponed until detection of VOC emission from the panel or other circumstances that warrant its construction.

The third LATER seal (Concept 6) is a concrete monolith placed after excavation of the DRZ and MB139. Should testing during the operational period show an inadequate seal by the first monolith, a second seal, such as another concrete monolith, can be emplaced to create a monitoring chamber.

Additional features of the alternative concepts are discussed in the following subsections.

3.1 Concept 1 — Rigid Sleeve

A rigid sleeve (see Figure 3-1A) is a cylindrical structure that consists of precast concrete and steel elements erected and grouted in place. The details of a similar design and construction are presented by Lin and Van Sambeek (1992a). The rigid sleeve is designed for ultimate salt-bearing loads from 2,500 to 3,500 psi (17 to 24 MPa). Its rigidity virtually eliminates further deformation of MB139 and is expected to promote healing of the salt DRZ around the excavation soon after installation. The sleeve will be installed in a section of opening with a circular cross section. Finite-element calculations have shown that a thickness of 4 ft (1.2 m) of salt between the mine floor and MB139 helps protect MB139 from uplift while allowing an opening of appropriate sizes to be placed in the WIPP stratigraphy (Lin and Van Sambeek, 1992a). In some concepts, emplacement of a rigid sleeve may require ramping for optimal seal location. The gas barrier in the operational period would consist of a stiffened steel-plate bulkhead, a steel-plate shell, a longitudinal membrane to prevent leakage from the host rock into the seal, and transverse membranes to prevent leakage along the interface of the seal and the host rock.

3.2 Concept 2 — Yielding Sleeve

The yielding sleeve concept illustrated in Figure 3-1B consists of a steel shell and a rigid-plastic backing system. The backing system is designed to allow creep closure of the excavation while maintaining constant back pressure on the excavation perimeter, as will be discussed in Section 4.4. The gas barrier of the yielding sleeve includes longitudinal and transverse membranes, similar to that of Concept 1. The rigid-plastic material for the backing can be made of lightweight foam concrete with perlite, vermiculite, or polystyrene pellets. The compressive strength and thickness of the rigid-plastic backing are designed for 150 psi (1 MPa) minimum back pressure at the time of installation and 300 psi (2 MPa) maximum back pressure after 35 years.

3.3 Concept 3 — Steel Ring with Inflated Tubes

The third concept of a yielding sleeve is illustrated in Figure 3-1C. It consists of several individual sleeves comprising a steel ring and an oval-shaped, inflatable, reinforced neoprene tube. The gas barrier inside the steel ring is a stiffened steel-plate bulkhead in the waste panel side of the individual sleeves similar to NOW Concepts 1 and 2. The inflated tubes provide back pressure for healing the DRZ behind the yielding sleeve. It is expected that the pressure inside the inflated tubes will be maintained at 200 psi (1.4 MPa) minimum and 300 psi (2 MPa) maximum during the operational period.

The sleeve can be installed one ring at a time to reduce the time delay between excavation and application of the back pressure. Conceptually, a construction time of 1 week for each ring and tube sleeve is possible (a total of 8 weeks). For faster installation, the access way could be excavated to the drift side face of the seal. Then a custom-made shearer could be used to excavate a groove to fit the inflated tube. The steel ring could be erected in segments over a deflated tube. In the unlikely event of tube failure, this construction method facilitates removal and replacement. Once a whole ring is formed, trued, and fixed together by bolts, the tube would be inflated with air to form a unit seal. Installation of this seal at the face of the advancing access drift could significantly reduce DRZ development. Using this construction technique, the time of unsupported excavation can be reduced to 1 week, which would further reduce formation of the DRZ and minimize deformation of MB139.

3.4 Concept 4 — Steel Ring Seals with Monitoring Chamber

Concept 4 is a LATER seal, which means that nothing is done in preparation for the operational seal until the panel is closed. This type of seal system (see Figure 3-2A) can also be readily adapted for use as a chamber to detect gases leaking from the waste panel. Because the excavated opening in the chamber will creep for 30 years or more, the back of the drift will likely have rock bolts installed. It is assumed that MB139 will have yielded and formed a network of leak passages, which may require grouting.

The waste-side steel ring is first erected and pressurized like the NOW Concept 3, except that a single ring and tube system is used. If leakage is detected, remedial measures are undertaken. For purposes of this study, it is assumed that initial monitoring indicates a second ring and tube system is warranted. At that point, excavation of the drift-side ring and installation of another steel plate are completed. The monitoring chamber can then be implemented.

This seal system requires monitoring and maintenance throughout the operational period that may be common to all panel seals but particularly important for the first-closed panel. The air pressure inside the inflated tube should be kept in the range of 200 to 300 psi (1.4 to 2.0 MPa). The monitoring chamber should be kept at a small negative pressure to ensure that any gases leaking into the chamber are collected, tested, and filtered for removal of contaminant before being vented to the atmosphere. A pressure relief valve or other appropriate monitoring equipment may be provided at the waste-side bulkhead to relieve or monitor excessive gas pressure generated inside the waste panel.

3.5 Concept 5 — Concrete Monoliths with Monitoring Chamber

The concept illustrated in Figure 3-2B has a monitoring chamber similar to Concept 4 but uses a pair of concrete monoliths instead of the steel ring system. The waste-side monolith is a simple cast-in-place concrete structure, and the drift-side monolith uses the inflated tubes. The reasoning for this concept is as follows:

- The single monolith is expected to be the simplest, least expensive seal that meets design criteria.
- If the plain monolith is inadequate, two inflated tubes can be provided in a drift-side concrete monolith to minimize leakage of clean air from the access drift into the monitoring chamber.

3.6 Concept 6 — Concrete Monolith with Excavation of MB139

Concept 6 (see Figure 3-2C) is a single concrete monolith cast in place after removal of the salt DRZ and damaged MB139 directly below the seal location. The main difference between Concepts 5 and 6 is that Concept 6 removes the salt DRZ and MB139 and replaces them with concrete, whereas Concept 5 relies on grout to stop leakage through MB139 if needed. Since concrete itself cannot be considered impervious, any monolith may need to be lined with longitudinal and transverse membranes. This concept recognizes that MB139 is likely to have become a significant leak passage. Excavation of salt DRZ is a typical practice for bulkhead emplacement in salt, especially where the bulkhead is designed to withstand the pressure of a hydrostatic head. A monitoring chamber similar to Concepts 4 and 5 could be added if warranted.

4.0 ROCK MECHANICS

4.1 Overview

Rock mechanics plays an important role in the design of an operational seal because of the interaction between the sleeve and the salt rock. Rock mechanics analyses provide information on the deformations and stresses as a result of the initial excavation and the later installation of a seal, and on the development and healing of the salt DRZ. Deformation information is required because salt creeps toward and into the opening in response to the disruption of the lithostatic stress state after excavation of an access drift. In the absence of any restraint, the creep deformation of the salt continues until the opening is completely closed and the stresses around the opening are able to return to a lithostatic state.

Concepts for the operational seals require different types of information about the deformation and potential damage of the rock around openings. The rock mechanics analyses explored several of these issues, namely:

- Is there a significant difference in terms of the developed DRZ for rigid versus yielding operational seals? That is, must the salt deformation be completely restrained to prevent damage or will a constantly applied, uniformly distributed pressure serve the same purpose, and if so, what magnitude is required?

- Is there a significant difference in terms of the developed DRZ for yielding-operational seals installed soon after excavation, compared to rigid-operational seals installed 5 or more years after excavation during panel sealing? That is, is there a benefit from actions taken NOW as opposed to actions taken LATER?

- If rigid operational seals are used, what is the possible variation in design load as the seal length changes? Earlier studies for the Alcove Gas Barrier explored this aspect of design, but only for lengths equal to or greater than the cross section. For this study, lengths much less than the cross-section dimension will be explored.

An assumption is that the operational seal restrains the salt creep and inhibits or completely arrests further accumulation of rock damage in both the salt and the interbeds. The stresses in the salt behind the operational seal will change after installation of the seal; the mean stress will increase and the deviatoric stresses will decrease (Lin and Van Sambeek, 1992; Van Sambeek et al., 1993a). Based on laboratory tests, this change in stress state is postulated to promote healing of damage within the DRZ in salt, but is not believed to affect the damage in the interbeds.

The operational seal analyses of the rock mechanics consist mainly of numerical modeling studies. Numerical modeling provides information on:

1. The development and extent of the DRZ after excavation of the drift but before seal installation.

2. The eventual loads to be borne by the rigid sleeve as a consequence of salt creep.

3. The response of the surrounding rock to the presence of the sleeve in terms of the healing of damage in the DRZ in salt and the arresting of further damage in the interbeds.

The first and third behaviors pertain to performance of the operational seal, whereas the second behavior determines the structural design load and its distribution for the rigid seal. The DRZ surrounding openings at the WIPP is known to have enhanced permeability and possible fractures. Therefore, the DRZ could prevent the operational seals from sealing the access drifts unless DRZ development can be reduced or remediated.

The DRZ can be divided into two areas: the DRZ in salt and the DRZ in the interbeds. The DRZ in salt develops as the salt undergoes dilational (volumetric increase) deformation from the unfavorable combination of high deviatoric stresses and low mean stress. As the salt deforms toward and into the opening, damage can occur in the interbeds (MB139 and the clay seams) in the form of deflection (bending) of MB139 and slippage across clay seams.

Studies of laboratory tests and the DRZ development in salt around underground openings at the WIPP have led to the conclusion that the DRZ can be understood and described in terms of the prevailing stress state in the salt (e.g., Van Sambeek et al., 1993b). Particular combinations of two stress invariants (the first invariant of the stress tensor, I_1, and the second invariant of the deviatoric stress tensor, J_2) cause salt specimens to dilate during laboratory creep tests. A limiting criterion for discriminating stress invariant combinations that cause dilation in laboratory tests of WIPP salt is:

$$\sqrt{J_2} = 0.27 I_1 \qquad (4\text{-}1)$$

This approximate mathematical limit surface separates the dilating and nondilating stress combinations. Whenever a stress condition causes dilation, the permeability is expected to be enhanced by microcracking in the salt. The relationship between the stress invariants and the degree of permeability enhancement is not yet known. The limit surface may also define the stress combinations that promote healing of preexisting microcracks. Healing of microcracks would lead to a reduction in permeability. This limit surface is used to determine the development and extent of the DRZ in salt on the basis of a calculated "damage factor."

The damage factor defined to quantify the state of the DRZ is the ratio of the calculated J_2 stress invariant and the J_2 stress invariant at the same I_1 on the limit surface. A damage factor value of 1.0 thus portrays a stress condition on the limit surface. A current damage factor greater than 1.0 signifies a stress state that has caused dilation in laboratory tests and likely will also cause dilation underground, causing a DRZ to develop. The amount of dilation (and hence permeability) is expected to increase with increasing damage factors. A damage factor less than 1.0 signifies that the stress state should not cause dilation. Moreover, if dilation has already occurred and the stress state has since changed, a current damage factor less than 1.0 signifies that healing is expected. As the damage factor decreases to smaller and smaller values, the expectancy for healing increases. Qualitatively, it is also expected that the lower the damage factor value, the faster that healing may occur.

The damage that occurs in the interbeds (MB139 and the clay seams) is believed to be primarily a consequence of strain (deformation). The strains or displacements are composed of both the elastic displacements that occur upon excavation of the opening and the displacements accumulated as the salt creeps. The most damaging deformation is from the creep of the salt. For instance, the salt below the floor of an opening moves toward and into the opening. MB139 is a relatively stiff anhydrite layer 3 ft (0.9 m) thick lying about 4 ft (1.2 m) below the floor of the mined openings. As the floor salt, particularly that below MB139, moves toward the opening, MB139 is compressed horizontally and deflected (bent) vertically. Preexisting, healed fractures in MB139 are expected to be opened or sheared by such deformation. The degree of damage in MB139 is, therefore, strongly related to the amount of creep deformation in the salt. With regard to MB139, a design criterion is to minimize the uplift and flexure of the anhydrite bed, which will limit damage to MB139 and reduce enhancement of permeability.

Similarly, the damage along clay seams arises from differential displacement across the clay seam primarily where a clay seam intersects the opening. It is not known whether such differential strain increases the permeability or if the permeability stays the same along the clay seam. The clay seams in the stratigraphy were modeled as frictional interfaces as described by Munson et al. (1989). As such, a certain level of differential strain must accumulate before the shear stress within the clay seam is sufficient to cause slip under the imposed normal stress.

The rock mechanics modeling was performed using the following assumptions:

- The initial stress state before excavation is lithostatic and equal to -2,140 psi (-14.76 MPa) at the WIPP horizon.
- Each excavation is sufficiently remote from other excavations to be considered a single, isolated room.
- The modeled region remains isothermal at 80°F (27°C).
- Excavations are created instantaneously.

Similar assumptions and modeling approaches have been used for model experiments and in situ measurement programs at the WIPP: South drift, Room G, and Room D (Munson and DeVries, 1991a, 1991b); heated rooms (Munson et al., 1990, 1991); heated pillar (Munson et al., 1988); and shaft closure measurements (Munson et al., 1992).

All of the rock mechanics modeling was performed using the finite-element computer code SPECTROM-32 (Callahan et al., 1989). The Munson-Dawson material model with maximum shear stress (Tresca) flow potential was used to model the salt. A two-dimensional plane-strain grid (107 m in height and 50 m in width) represented the stratigraphy and openings. Boundary conditions included rollers on three sides with top free and constant stress at the inside of the excavation. Four-noded elements were used in the plane-strain models of the yielding sleeves. Anhydrite and polyhalite were modeled with a Drucker-Prager elastic-plastic criterion.

4.2 Rock Properties

The stratigraphy and mechanical behavior (material models and properties for halite, argillaceous halite, anhydrite, polyhalite, and clay) of the rock mass surrounding the excavations were modeled as shown in the preliminary data base document (Bailey et al., 1992b) for the WIPP sealing system. For salt, the Munson-Dawson multimechanism constitutive model with parameter values determined from laboratory tests and field data verification analyses (Munson et al., 1992) was used in the rock mechanics modeling.

4.3 Rigid Seal Analysis

The purpose of the rigid seal analyses was to determine the design load (liner loading imposed by the salt formation on a rigid structure). A load is imposed on the structure because the structure restrains the inward creep of the salt causing a back stress (radial pressure) to develop between the structure and the surrounding salt. The magnitude of this pressure depends on the length of the structure and the amount of time that the structure has restrained the inward creep of salt. The magnitude of loading within the design life affects the design requirements of the structure. For the analyses, axisymmetric modeling with an all-salt medium was used to evaluate the effects of length on the structure. Plane-strain analyses could not be used because they assume an infinitely long structure. On the other hand, axisymmetric analyses cannot include the stratigraphy.

The rigid operational seal has a circular configuration with an outside diameter of 16 ft (4.8 m). The rigid sleeve was modeled as a solid inclusion constructed from a material with a Young's modulus of 5.7×10^6 psi (39.3 GPa) and a Poisson's ratio of 0.21. Immediate contact was assumed between the sleeve and the salt at the time of installation and the bond between the sleeve and salt was assumed to be infinitely strong.

4.3.1 Sleeve Geometries

Four different lengths of rigid sleeves were modeled to assess the liner loading and stress concentrations. A sketch of the geometric configuration is shown in Figure 4-1. Only one-half of the rigid seal structure was actually modeled because of symmetry about a vertical plane through the center of the seal. Therefore, results are shown as varying from the seal midlength toward the ends. A mirror-image distribution of the result is expected on either side of the midlength.

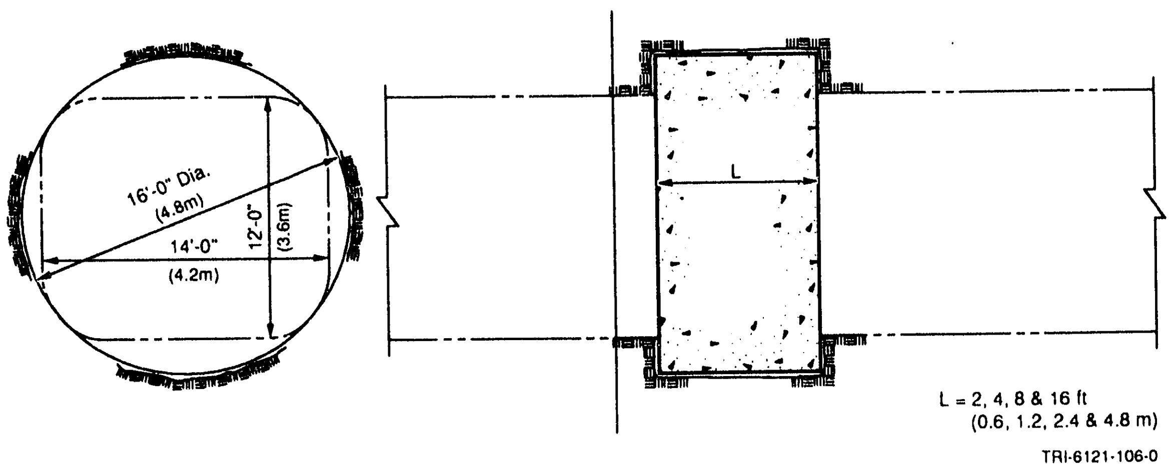


Figure 4-1. Schematic rigid seal for operational period.

4.3.2 Modeling Sequence

The rock mechanics analyses were performed with the following sequence:

- The drift was instantaneously excavated.
- The salt surrounding the excavation was allowed to creep for 90 days before installation of the rigid seal structure.
- The rigid seal structure was installed in the excavation.
- The salt around the excavation and rigid sleeve was allowed to creep to a time of 10 years.

4.3.3 DRZ and Radial Loading

Two modeling results are of principal concern for each of the rigid operational seal lengths: (1) the transient extent of the DRZ in the salt, and (2) radial loading on the rigid sleeve. These two quantities are discussed below for the four lengths of the rigid operational seals.

A qualitatively similar DRZ develops in the salt for each rigid sleeve length. Following the instantaneous excavation, the DRZ based on the elastic stresses extends into the salt for a distance of about 1 ft (0.3 m). After 3 months of unrestrained creep, the extent of the DRZ is reduced because of stress redistribution. Axisymmetrical modeling neglects the bedded stratigraphy at the WIPP; therefore, additional considerations of the DRZ are presented later in this section for different cross sections.

After installation of the rigid operational seal, the salt adjacent to the rigid seal begins to heal in response to the changing stresses (i.e., the damage factor drops below 1.0). The region of healing expands and the DRZ decreases in size throughout the simulation. However, the DRZ surrounding the unlined portion of the drift is virtually unaffected by the presence of the rigid seal and continues to develop naturally.

The transient radial loading on the rigid seal for the 16-ft-long (4.8-m) seal is illustrated in Figure 4-2. The transient character of the radial loading for each of the other rigid seal lengths is similar from the perspective of axisymmetrical modeling. The radial loading increases with time to a relatively steady magnitude within about 5 years. For example, the maximum radial loading on the 16-ft-long seal increases to 2,900 psi (20 MPa) after 1/2 year and to 4350 psi (30 MPa) after 10 years.

Figure 4-3 illustrates the maximum radial loading on a rigid seal as a function of seal length at 1/2 year and 10 years after excavation. The radial loading on rigid plugs is highest for the shortest seal, decreasing as the seal length increases. For example, the maximum radial stress after 10 years on a 2-ft (0.6-m) seal is calculated to be over 14,500 psi (100 MPa), whereas the maximum radial stress on a 16-ft (4.8-m) liner is about 4,350 psi (30 MPa).

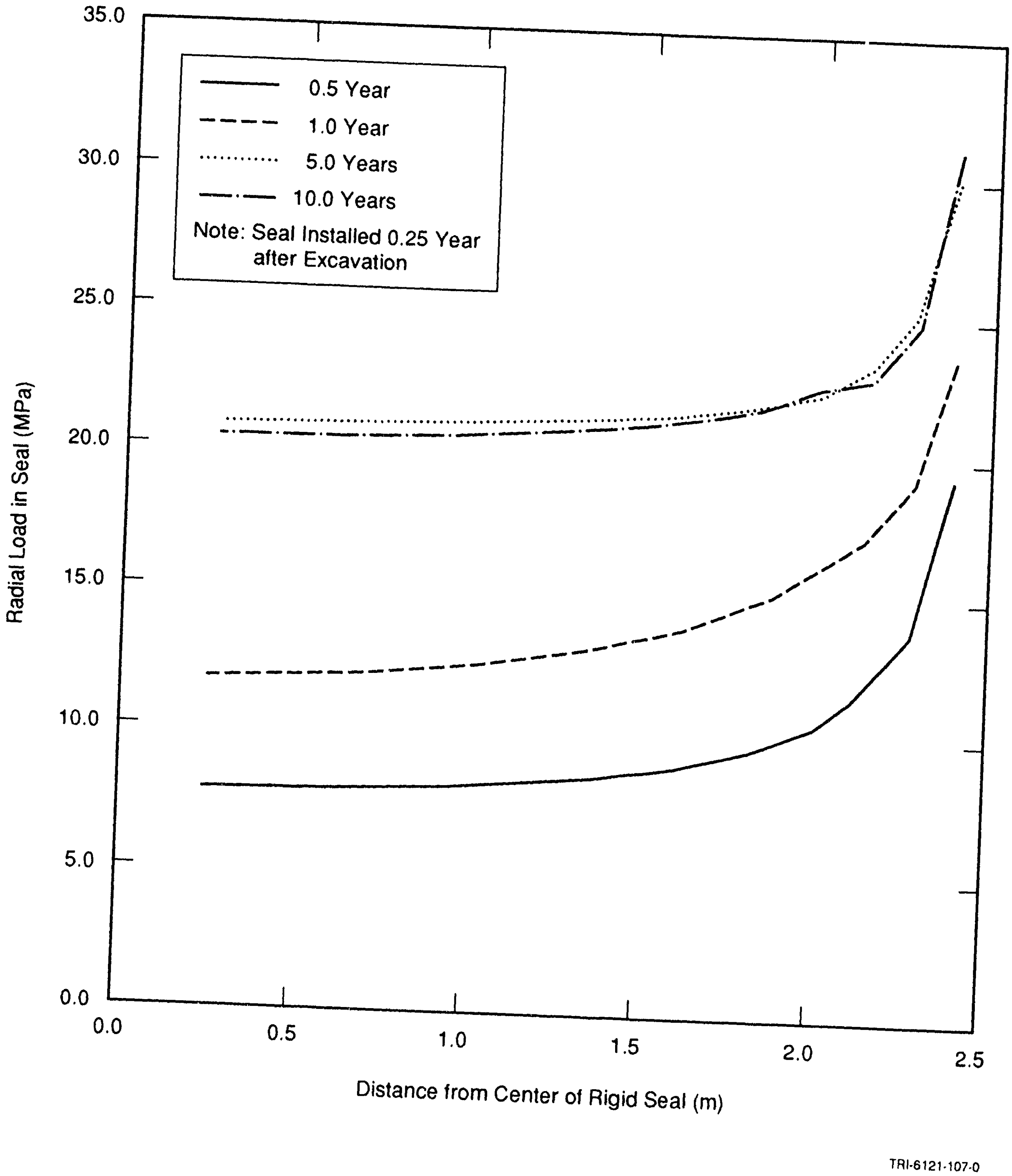


Figure 4-2. Radial loading from an axisymmetrical model.

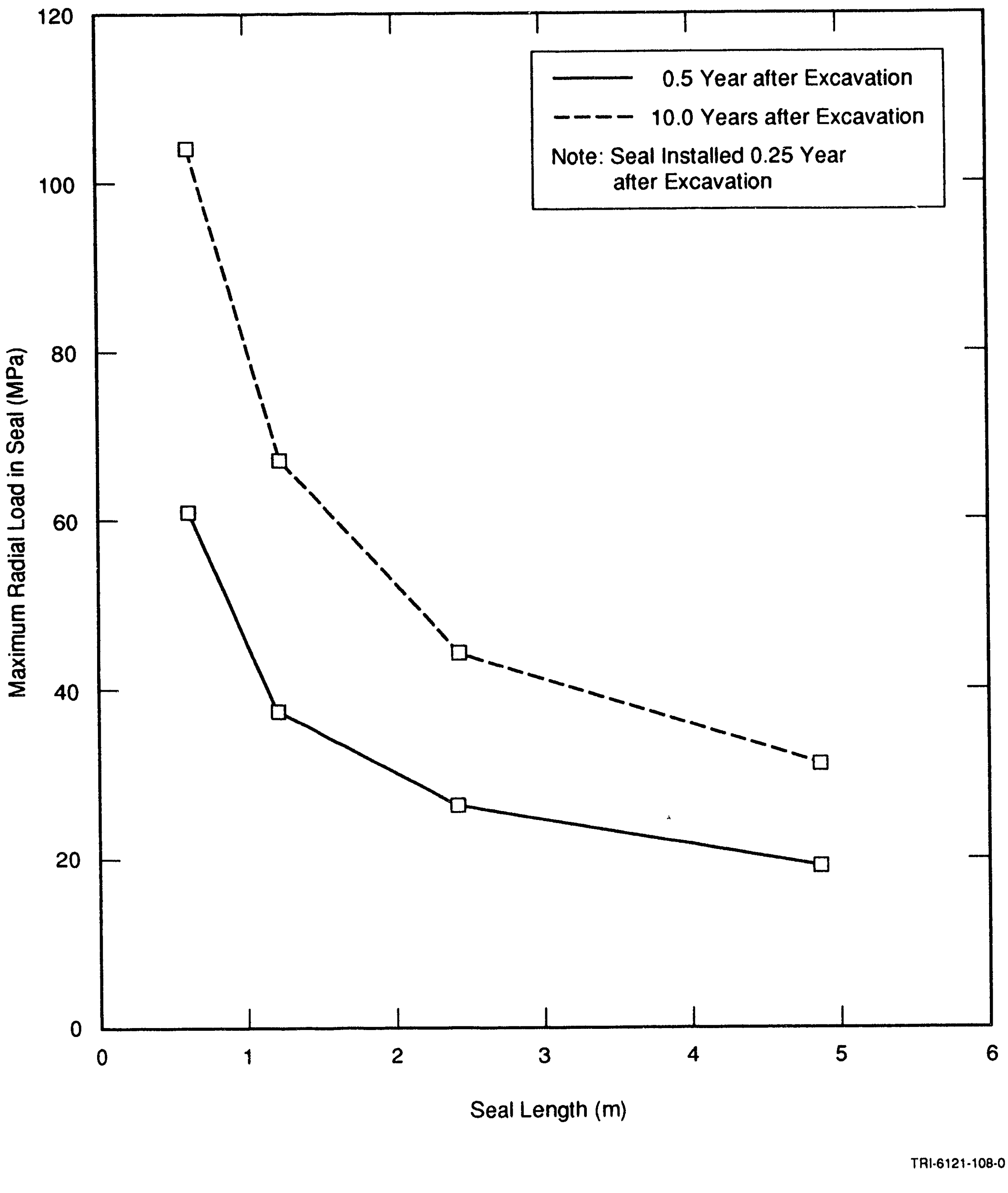


Figure 4-3. Maximum radial loading on the rigid operational seals.

4.4 Yielding Sleeve Analysis

The purpose of the yielding sleeve analyses was to provide information, so the relative merits of installing yielding sleeves soon after excavation could be compared to installing rigid structures either soon after excavation or later upon panel closure. The analyses performed were plane-strain analyses (cross-sectional analyses) that accounted for the WIPP stratigraphy (i.e., included the MB139 and clay seams) and three potential shapes for the openings.

The yielding-sleeve concept allows some load to develop on the seal lining such that a predefined amount of back pressure is exerted on the perimeter of the salt excavation. Because the predefined loading from the yielding sleeve can be small, the structural requirements for the sleeve are significantly reduced, yet some confinement is provided to the salt, which in turn reduces the extent of the salt DRZ and the uplift of MB139. Two predefined back pressures were considered in the analyses: 150 and 300 psi (1 and 2 MPa).

4.4.1 Sleeve Geometries

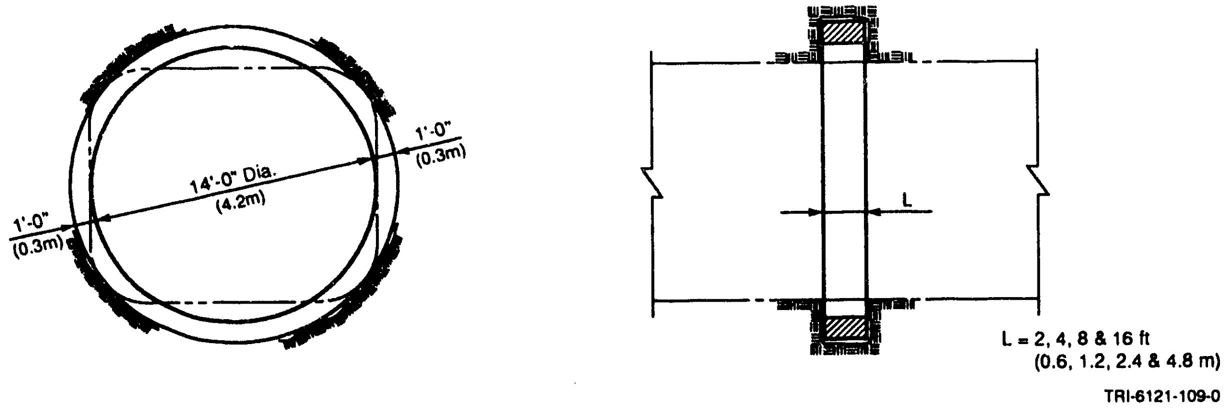
The three opening geometries considered in the evaluation of the yielding sleeve are illustrated in Figure 4-4: a circular, a rectangular, and a horseshoe shape (circular roof with flat floor). These same shapes were analyzed in previous studies, and the advantages and disadvantages of the shapes are discussed by Lin and Van Sambeek (1992). In summary, the circular shape is hypothesized to be the optimum shape for restraining the uplift of MB139. The rectangular shape is the easiest to mine, but it allows the most flexure of MB139. The horseshoe shape is believed to provide greater restraint to the uplift of MB139 without seriously impacting the mining. The shapes are compared in terms of the extent of the DRZ (dilation zone) in salt around the opening, the uplift (flexure) of MB139, and the closure of the drift (another measure of possible damage to the salt and interbeds). Two values of uniformly applied pressure were used in the analyses: 150 and 300 psi (1 and 2 MPa). The lower magnitude was selected because such a pressure causes significant consolidation of crushed salt when applied for long periods. By analogy, the DRZ is similar to a crushed salt with high fractional density. The upper magnitude was selected as a reasonable design pressure that could be resisted by a relatively light shell for ease of construction and cost saving (see Section 5.0). Recall that the purpose of the yielding sleeve is to limit damage to the salt and provide a back pressure for healing less expensively than with a rigid sleeve.

The yielding seal model is represented in the simplest form possible: a uniformly distributed boundary pressure along the perimeter of the opening. The constant-pressure boundary condition simulates the yield stress required to deform the yielding sleeve structure as a perfectly plastic material.

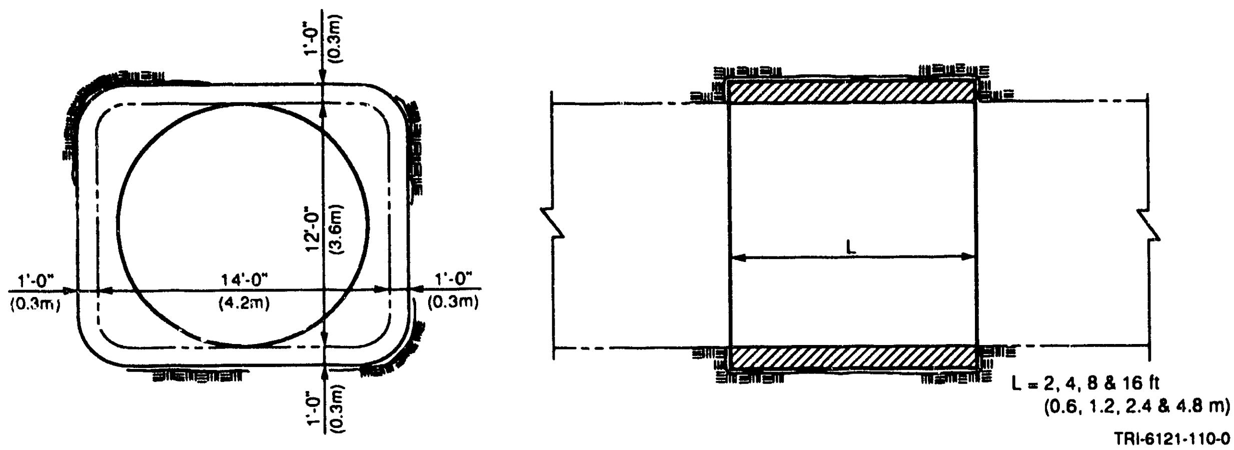
4.4.2 Modeling Sequence

The rock mechanics analyses of each of the yielding sleeves geometries were performed in the following sequence:

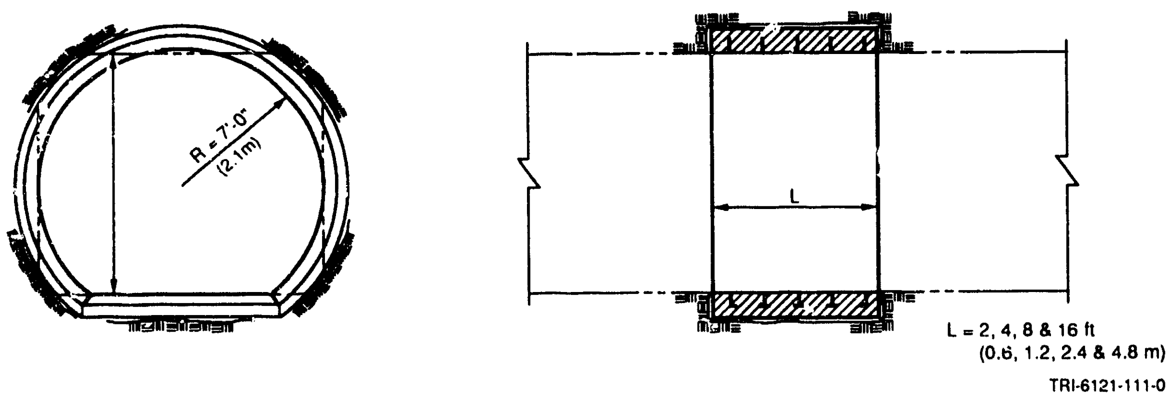
- The drift was excavated instantaneously.
- The salt around the excavation was allowed to deform unrestrained until the seal was installed.



A. Cylindrical seal.



B. Rectangular seal.



C. Horseshoe seal.

Figure 4-4. Typical yieldi, g seal for operational period in different sections.

- Seal installation times of 1 and 3 months were used for the circular geometry. A seal installation time of 3 months was used for the rectangular and horseshoe-shaped geometries.
- The installation of the yielding seal was simulated as an instantaneous application of a pressure boundary condition.
- The salt around the excavation and yielding seal was allowed to deform for 10 years.

The yielding sleeve is modeled differently from the rigid seal. Deformation in the cross section of the drift is the more important consideration for modeling. Plane strain is assumed along the axis of the drift.

4.4.3 Modeling Results

Three principal quantities from the model output are evaluated for each of the yielding seals: (1) the transient extent of the salt DRZ, (2) the uplift of MB139, and (3) closure of the drift at the seal location. These three quantities are discussed below for each of the three modeled cross sections.

4.4.3.1 SALT DRZ

4.4.3.1.1 Circular Cross Section

The salt DRZ (as depicted through the contours of a damage factor, see Section 4.1) is shown in Figure 4-5 for the circular drift cross section at times equal to drift excavation, 3 months, 1 year, and 10 years after drift excavation for the condition when no seal of any kind is installed. The salt DRZ initially extends about 1 ft (0.3 m) into the salt. At the time when a seal would be emplaced (1 to 3 months after excavation), the DRZ has grown by about 50 percent in the floor and along Clay Seam F. If the circular cross section is left open for 10 years, the salt DRZ extends approximately 2 ft (0.6 m) into the salt.

Figure 4-6 illustrates the salt DRZ immediately after installation of the 150 and 300 psi (1 and 2 MPa) yielding seals. If a yielding seal with a yield strength of 150 psi (1 MPa) is installed, a small DRZ persists throughout the ten years following excavation but is confined to small cross-sectional areas in the floor, roof, and rib. Installation of a yielding seal with a yield strength of 300 psi (2 MPa) eliminates the stress conditions causing the salt DRZ.

4.4.3.1.2 Rectangular Cross Section

The salt DRZ (as depicted through the contours of damage factor) for the rectangular drift cross section at times equal to drift excavation, 3 months, 1 year, and 10 years after drift excavation is illustrated in Figure 4-7 for the condition when no seal of any kind is installed. The salt DRZ initially extends over 2 ft (0.6 m) into the salt. At the time when a seal would be emplaced, the DRZ has grown in the floor and back to MB139 and Clay Seam F, respectively. If the rectangular cross section is left open for 10 years without any seal installed, the salt DRZ extends approximately 3 ft (1 m) into the rib.

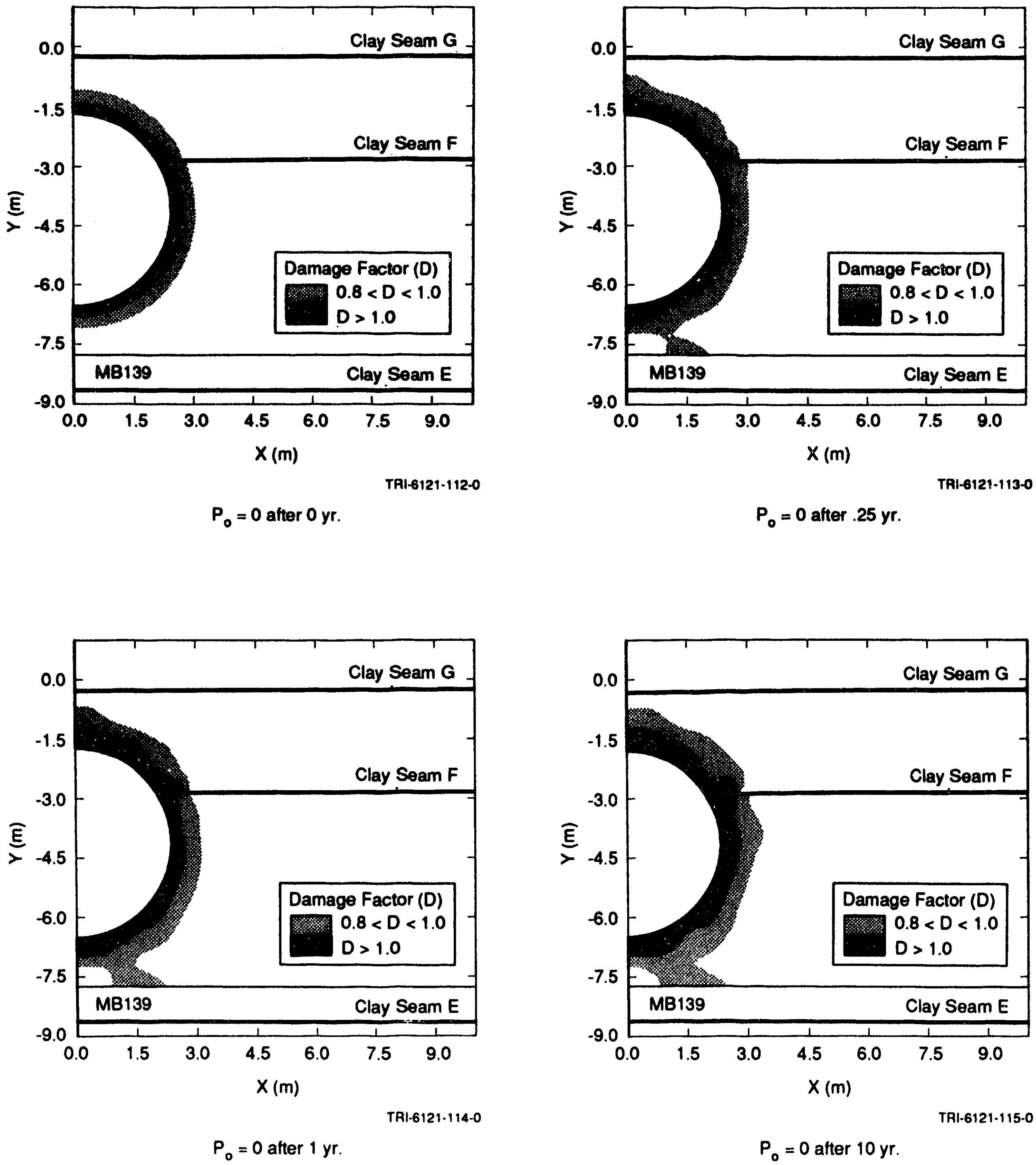
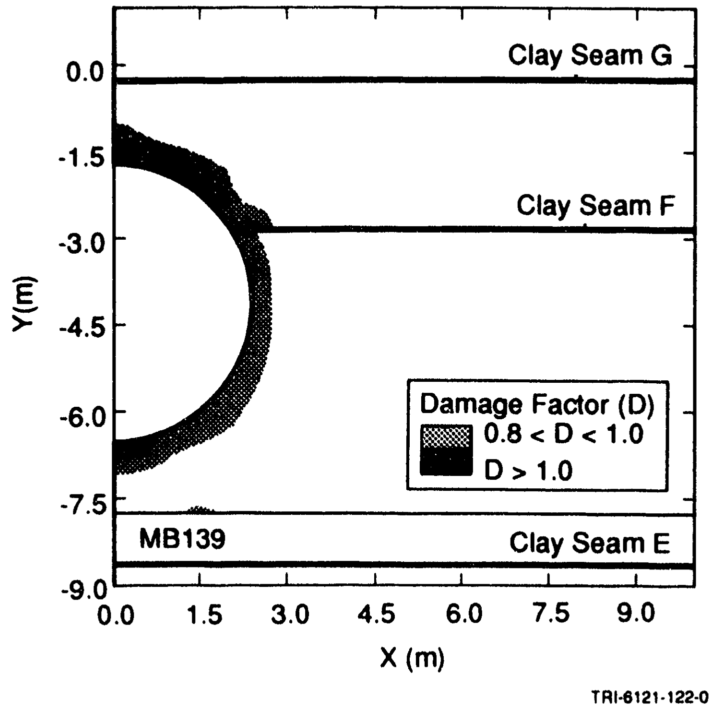
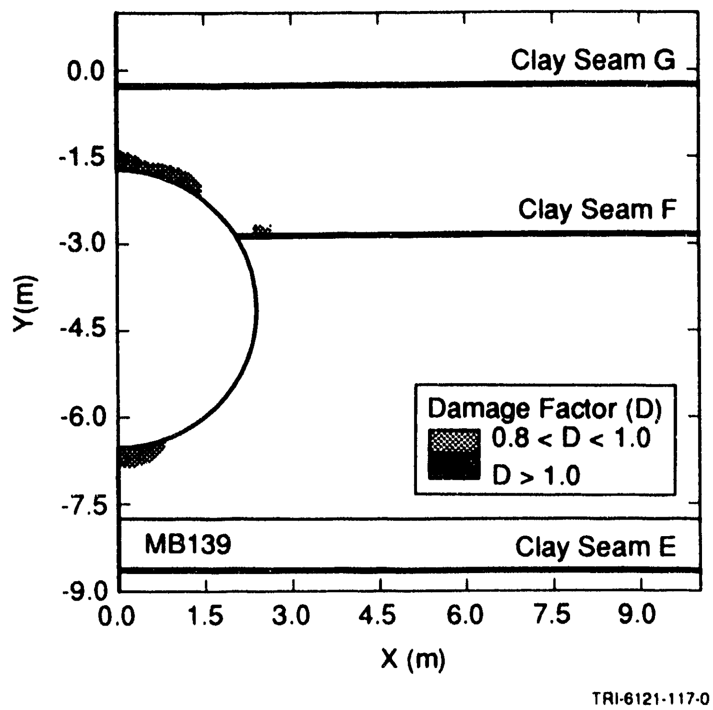


Figure 4-5. Development of the salt damage zone for a circular cross-sectional access drift.



P_o = 1 MPa after 0.25 yr.



P_o = 2 MPa after 0.25 yr.

Figure 4-6. Illustration of the salt damage zone for a circular cross-sectional access drift immediately following installation of a 150 psi or 300 psi (1 or 2 MPa) yielding sleeve (3 months after drift excavation).

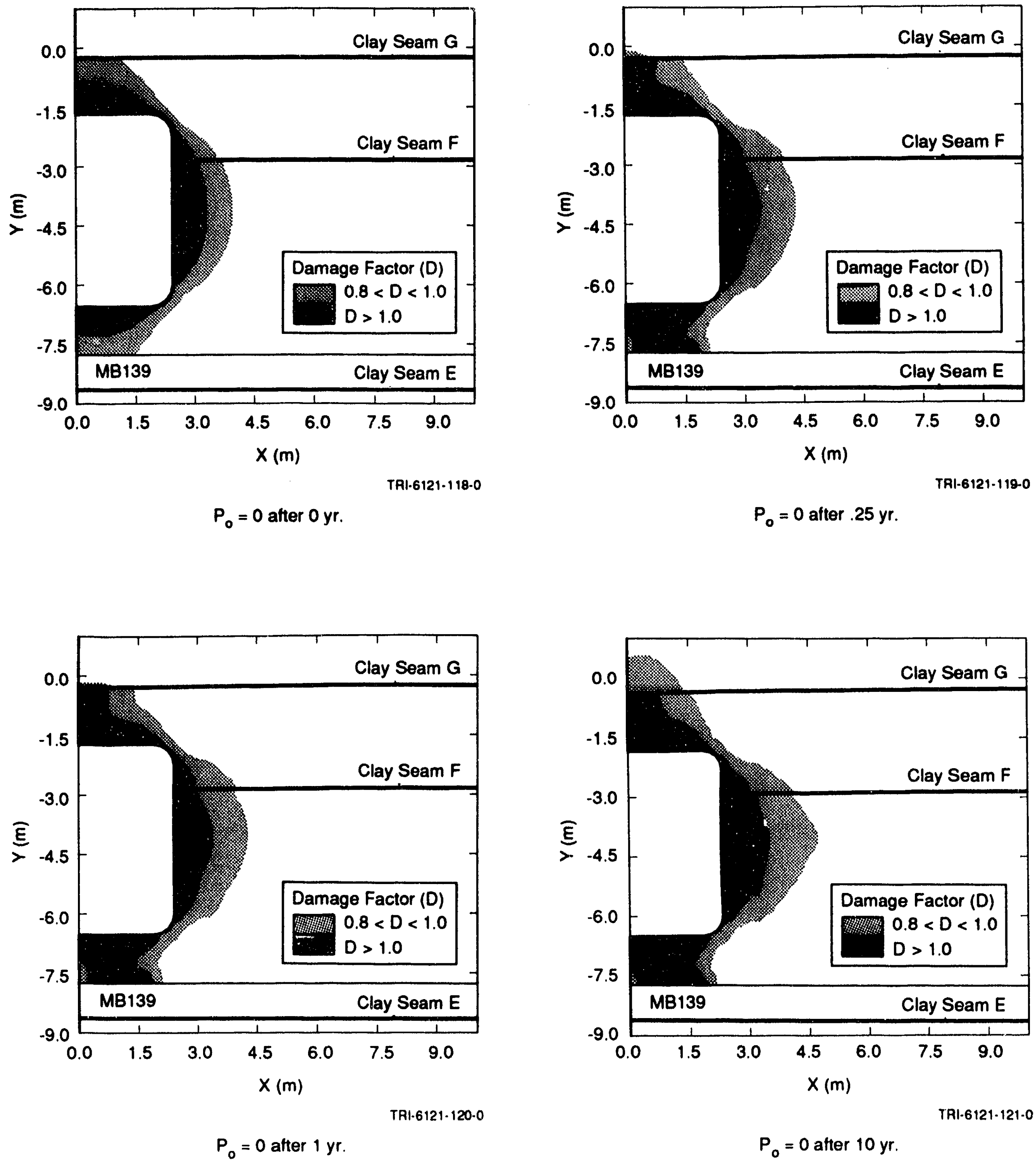


Figure 4-7. Development of the salt damage zone for a rectangular cross-sectional access drift.

Figure 4-8 illustrates the DRZ immediately after installation of the 150 and 300 psi (1 and 2 MPa) yielding seals. If a yielding seal with a yield strength of 150 psi (1 MPa) is installed, a salt DRZ region persists throughout the 10 years following excavation both in the floor near MB139 and in the rib near Clay Seam F. Installation of a yielding seal with a strength of 300 psi (2 MPa) almost immediately eliminates the stress conditions causing the salt DRZ.

4.4.3.1.3 Horseshoe Cross Section

The salt DRZ (as depicted through the contours of damage factor) for the horseshoe-shaped drift cross section at times equal to drift excavation, 3 months, 1 year, and 10 years after drift excavation is illustrated in Figure 4-9 for the condition when no seal of any kind is installed. The salt DRZ initially extends about 1 ft (0.3 m) into the salt back and rib and approximately 2 ft (0.6 m) into the floor. At the time (0.25 yr.) when a seal would be emplaced, the DRZ has developed through the salt in the floor to MB139. If the horseshoe-shaped cross section is left open for 10 years without any seal installed, the salt DRZ extends approximately 2 ft (0.6 m) into the salt in the rib and back and contains almost all of the salt between the floor of the drift and MB139.

Figure 4-10 illustrates the DRZ immediately after installation of the 150 and 300 psi (1 and 2 MPa) yielding seals. If a yielding seal with a yield strength of 150 psi (1 MPa) is installed, a salt DRZ persists in the floor of the drift throughout the 10 years following excavation. Installation of a yielding seal with a strength of 300 psi (2 MPa) eliminates the stress conditions causing a DRZ within 1 year.

4.4.3.1.4 Summary

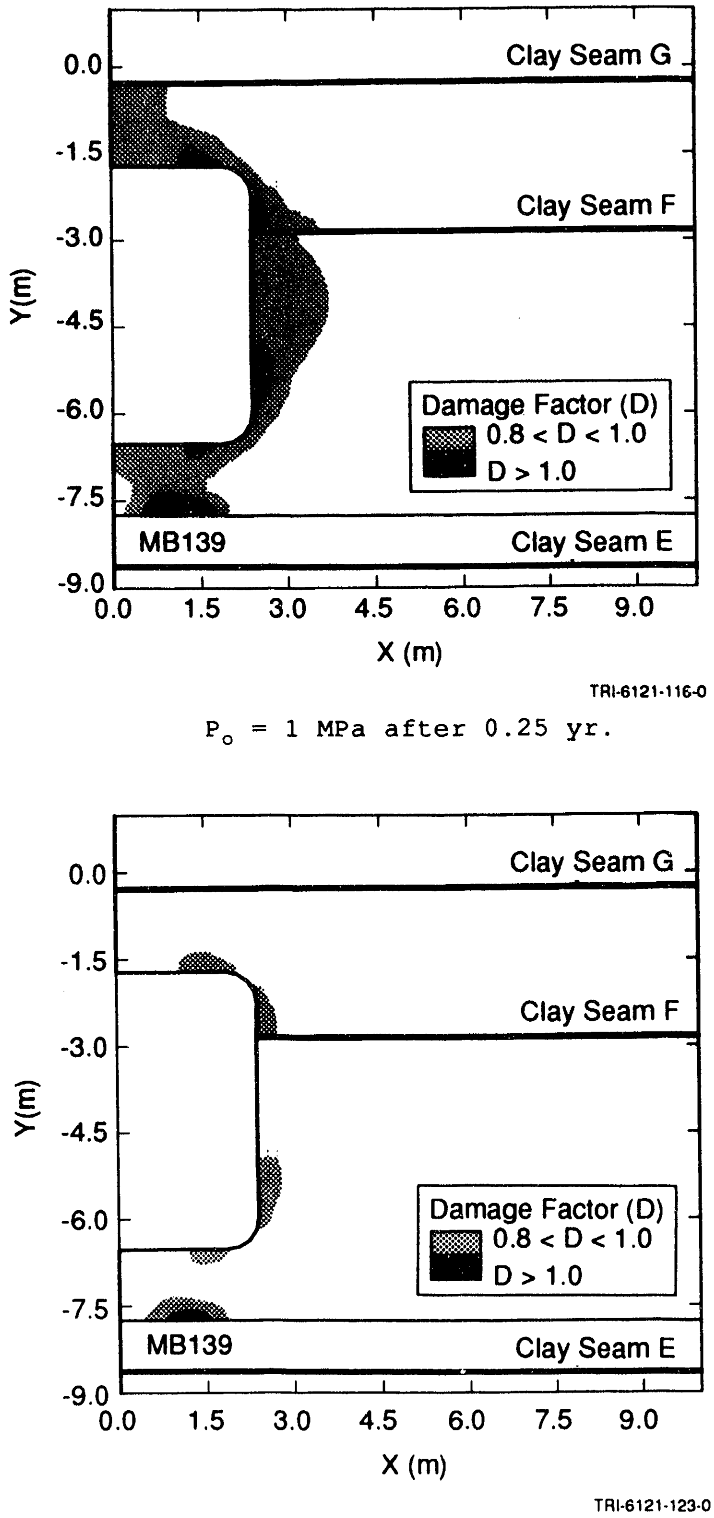
The salt damage zone consists of a primary DRZ formed immediately after excavation and a secondary DRZ that results from the salt creep and subsequent load redistribution. The initial DRZ extends the smallest distance into the surrounding salt for the circular cross section. The simulations with the circular cross section indicate that the secondary DRZ does not reach MB139 even if a yielding seal is not installed. However, in the simulations of the rectangular- and horseshoe-shaped cross sections, the secondary DRZ extends down to MB139 within 3 months after excavation.

In each of the three drift cross sections evaluated, a region of salt experiencing damage persisted throughout the period of 10 years after drift excavation when a yielding seal with a strength of 150 psi (1 MPa) was installed. Installation of a yielding seal with a strength of 300 psi (2 MPa) virtually eliminated the stress conditions causing the salt DRZ for all three cross-sectional shapes.

4.4.3.2 MB139 UPLIFT

4.4.3.2.1 Circular Cross Section

The transient uplift of the upper surface of MB139 along the center line of the circular cross section is illustrated in Figure 4-11. Included in the figure are results from an analysis without a yielding seal and analyses with yielding-seal strengths of 150 and 300 psi (1 and 2 MPa) with an installation time of 1 month or 3 months.



P_o = 1 MPa after 0.25 yr.

P_o = 2 MPa after 0.25 yr.

Figure 4-8. Illustration of the salt damage zone for a rectangular cross-sectional access drift immediately following installation of a 150 or 300 psi (1 or 2 MPa) yielding sleeve (3 months after drift excavation).

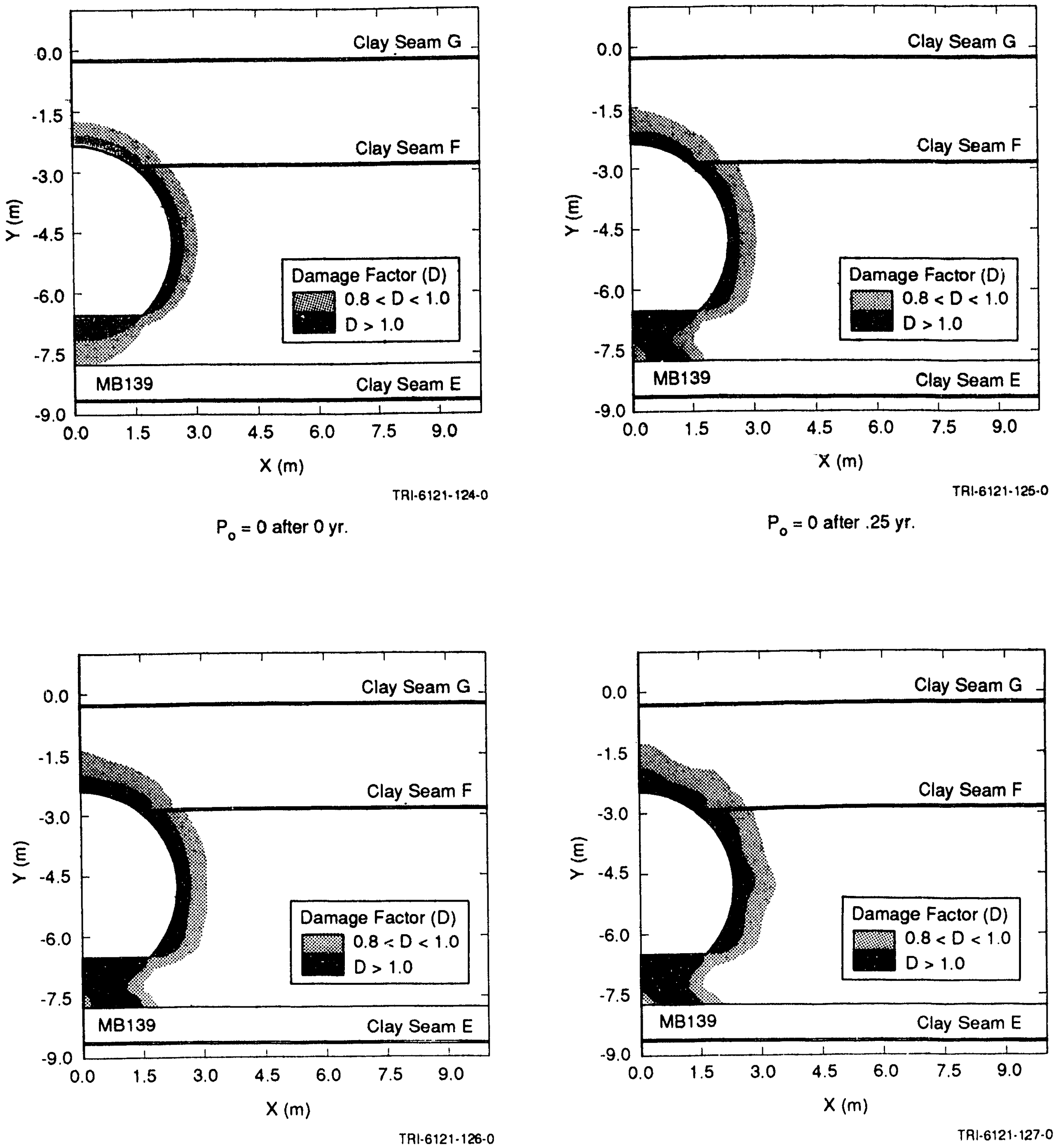
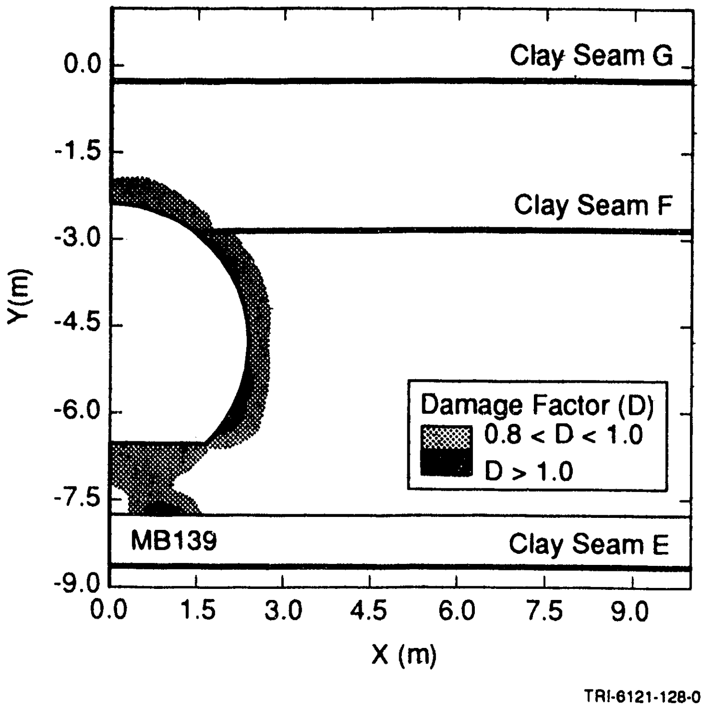
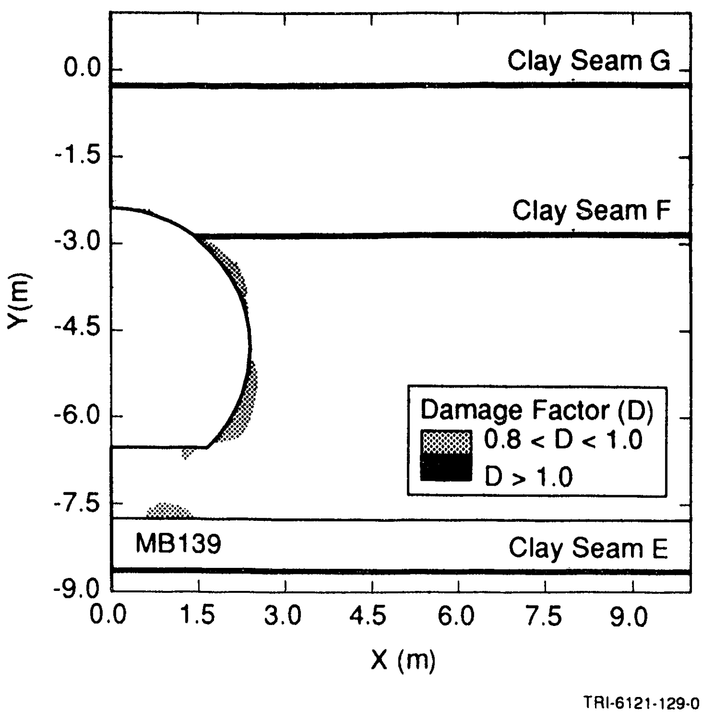


Figure 4-9. Development of the salt damage zone for a horseshoe cross-sectional access drift.



P_o = 1 MPa after 0.25 yr.



P_o = 2 MPa after 0.25 yr.

Figure 4-10. Illustration of the salt damage zone for a horseshoe cross-sectional access drift immediately following installation of a 150 or 300 psi (1 or 2 MPa) yielding sleeve (3 months after drift excavation).

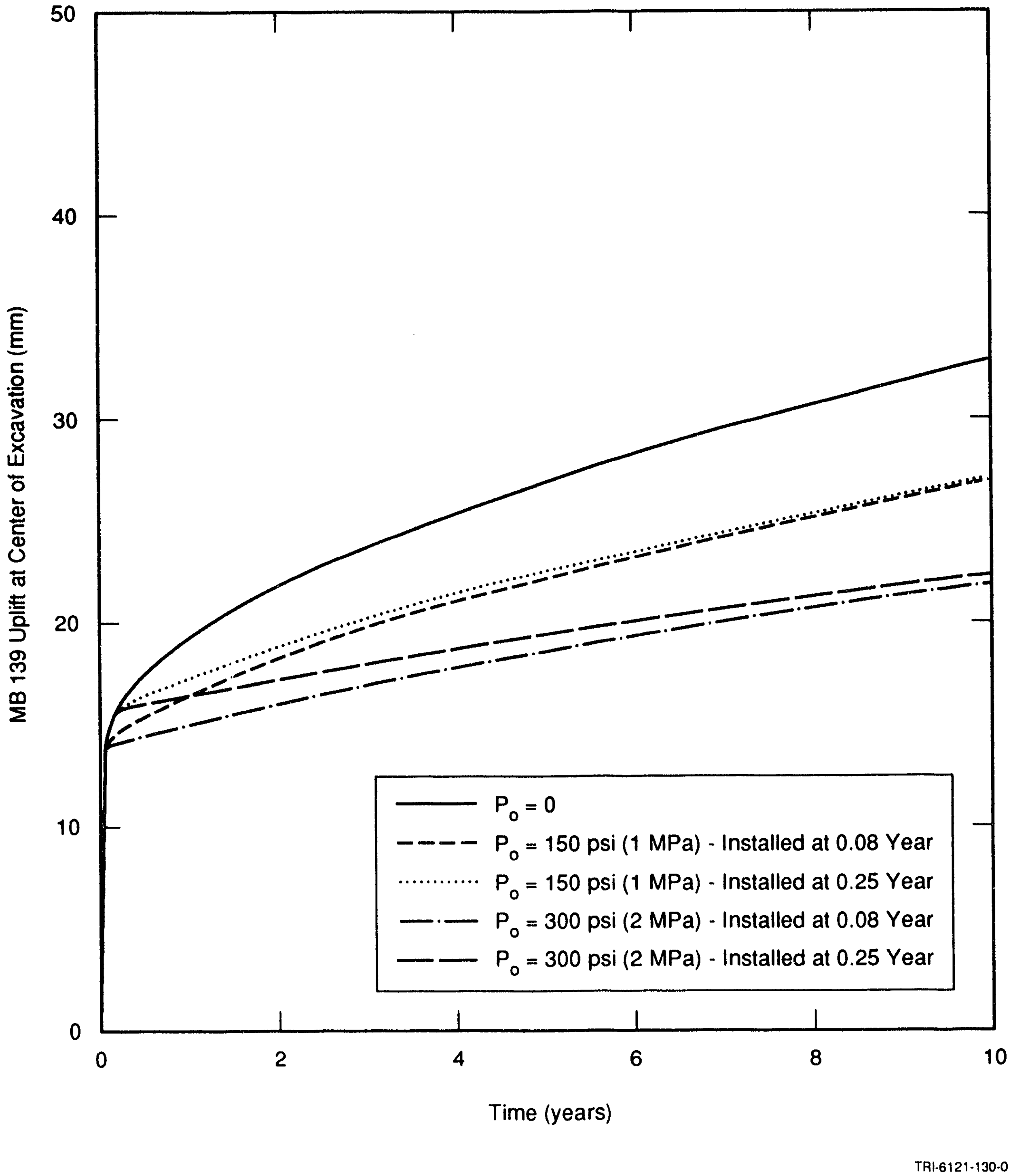


Figure 4-11. MB139 uplift for no yielding seal and yielding seal strengths of 150 and 300 psi (1 and 2 MPa) for a drift of the circular cross section.

Before installation of the seal, MB139 experiences about 0.5 in. (14 mm) of uplift after 1 month, compared to about 0.6 in. (16 mm) after 3 months. If no seal is installed in the circular-shaped drift, MB139 experiences total uplift of about 1.3 in. (33 mm) in 10 years. If a yielding seal with a yield strength of 150 psi (1 MPa) is installed, MB139 is uplifted about 1.1 in. (27 mm) in 10 years regardless of whether the seal is installed at 1 month or 3 months. If a yielding seal with a yield strength of 300 psi (2 MPa) is installed, the uplift of MB139 after 10 years is reduced to about 0.9 in. (22 mm) for both the one-month and three-month installation times.

4.4.3.2.2 Rectangular Cross Section

The transient uplift of the upper surface of MB139 along the center line of the rectangular cross section is illustrated in Figure 4-12 for a model without a yielding seal and models with yielding-seal strengths of 150 and 300 psi (1 and 2 MPa). Before installation of the seal 3 months after room excavation, MB139 experiences about 0.8 in. (21 mm) of uplift.

If no seal is installed in the rectangular-shaped drift, MB139 experiences an additional uplift of about 0.9 in. (23 mm) in 10 years. Installation of a yielding seal 3 months after excavation reduces the postinstallation uplift of MB139 to 0.6 and 0.4 in. (15 and 9 mm) for yield strengths of 150 and 300 psi (1 and 2 MPa), respectively.

4.4.3.2.3 Horseshoe Cross Section

The transient uplift of the upper surface of MB139 along the center line of the horseshoe-shaped cross section is illustrated in Figure 4-13 for no yielding seal and for yielding-seal strengths of 150 and 300 psi (1 and 2 MPa). Before installation of a yielding seal 3 months after excavation, MB139 experiences about 0.7 in. (17 mm) of uplift.

If no seal is installed in the horseshoe-shaped drift, MB139 experiences an additional uplift of about 0.7 in. (17 mm) in 10 years. Installation of a yielding seal 3 months after excavation reduces the postinstallation uplift of MB139 to 0.5 and 0.3 in. (12 and 7 mm) for yield strengths of 150 and 300 psi (1 and 2 MPa), respectively.

4.4.3.2.4 Summary

As hypothesized, MB139 uplift is greatest for the rectangular cross section and least for the circular cross section. The reduction in uplift provided by the yielding seal as a percentage of the uplift without a yielding seal is nearly identical for each of the three drift shapes. The 150 psi (1 MPa) yielding seal reduces the uplift by approximately 18 percent, and the 300 psi (2 MPa) yielding seal reduces the uplift by 33 percent.

Reducing the installation time from 3 months to 1 month has a minimal effect on the uplift of MB139 at later times. Despite the preinstallation uplift reduction from 0.6 in. (16 mm) to 0.5 in. (14 mm) for the circular cross section, the total uplift of MB139 after 10 years is reduced less than 0.02 in. (0.5 mm) by changing the installation time from 3 months to 1 month for both the 150 and 300 psi (1 and 2 MPa) yield-strength seals.

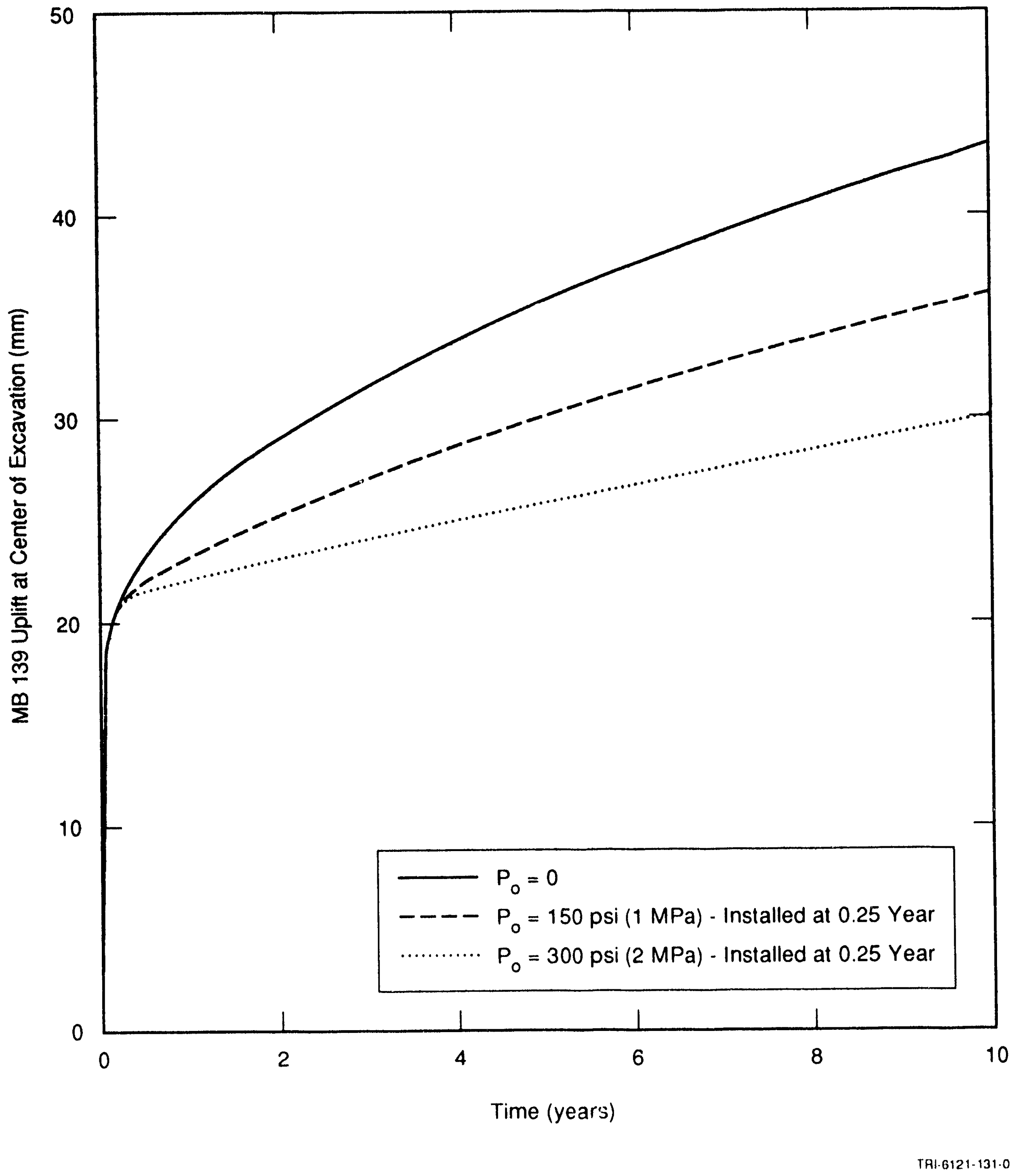


Figure 4-12. MB139 uplift for no yielding seal and yielding seal strengths of 150 and 300 psi (1 and 2 MPa) for a drift of the rectangular cross section.

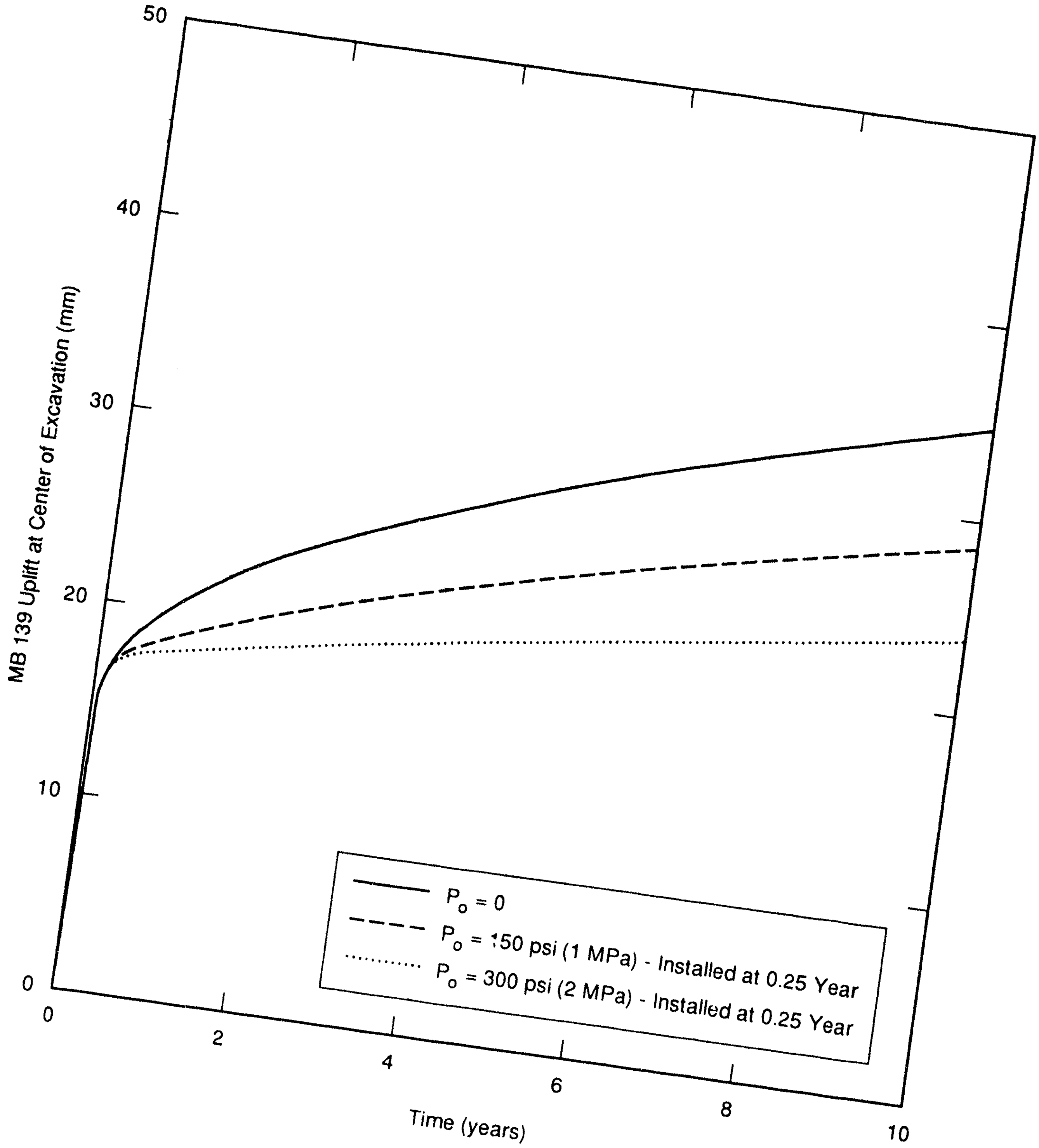


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Figure 4-13. MB139 uplift for no yielding seal and yielding seal strengths of 150 and 300 psi (1 and 2 MPa) for a drift of the horseshoe cross section.

4.4.3.3 DRIFT CLOSURE

4.4.3.3.1 Circular Cross Section

The calculated volumetric closure (loss in cross-sectional area for a unit length of drift) without a seal and with yielding seals having strengths of 150 and 300 psi (1 and 2 MPa) and installation times of 1 month and 3 months are illustrated in Figure 4-14. The circular cross-sectional drift loses about 2.75 percent of its volume within 1 month and about 3.25 percent within 3 months if no seal is installed; within 10 years it experiences 8.5 percent closure. The total drift closure for the 10-year period for seals with yield strengths of 150 and 300 psi (1 and 2 MPa) are approximately 6.75 percent and 5.25 percent, respectively, regardless of whether the seal is installed at 1 month or 3 months after excavation.

4.4.3.3.2 Rectangular Cross Section

The volumetric closure of the rectangular-shaped drift without a seal and with yielding seals having strengths of 150 and 300 psi (1 and 2 MPa) are illustrated in Figure 4-15. The drift experiences more than 3 percent room closure before the seal is installed. If no seal is installed, the drift experiences an additional 6 percent of closure within 10 years after excavation. Installation of a yielding seal reduces the postinstallation volumetric closure to about 4 percent and 2 percent for yield strengths of 150 and 300 psi (1 and 2 MPa), respectively.

4.4.3.3.3 Horseshoe Cross Section

The volumetric room closure of the horseshoe-shaped cross-sectional drift with no seal and with yielding seals having strengths of 150 to 300 psi (1 and 2 MPa) is illustrated in Figure 4-16. The drift experiences more than 3 percent room closure before the seal is installed. If no seal is installed, the drift experiences an additional 6 percent of closure within 10 years after excavation. Installation of a yielding seal reduces the postinstallation volumetric closure to about 4 percent and 2 percent for yield strengths of 150 and 300 psi (1 and 2 MPa), respectively.

4.4.3.3.4 Summary

The volumetric drift closure without a yielding seal is greater for both the rectangular- and horseshoe-shaped drifts than for the circular-shaped drift. Installation of a yielding seal resulted in nearly identical reductions in the maximum amount of closure for each of the three shapes: the 150 psi (1 MPa) yielding seal reduced closure by approximately 20 percent and the 300 psi (2 MPa) yielding seal reduced it by approximately 40 percent.

Changing the installation time from 3 months to 1 month for the circular cross section had a minimal effect on room closure. The preinstallation room closure was reduced from 3.25 percent to 2.75 percent. Total closure over the 10-year modeling period was reduced less than 0.25 percent by reducing the installation time from 3 months to 1 month for both the 150 and 300 psi (1 and 2 MPa) yield strength sleeves.

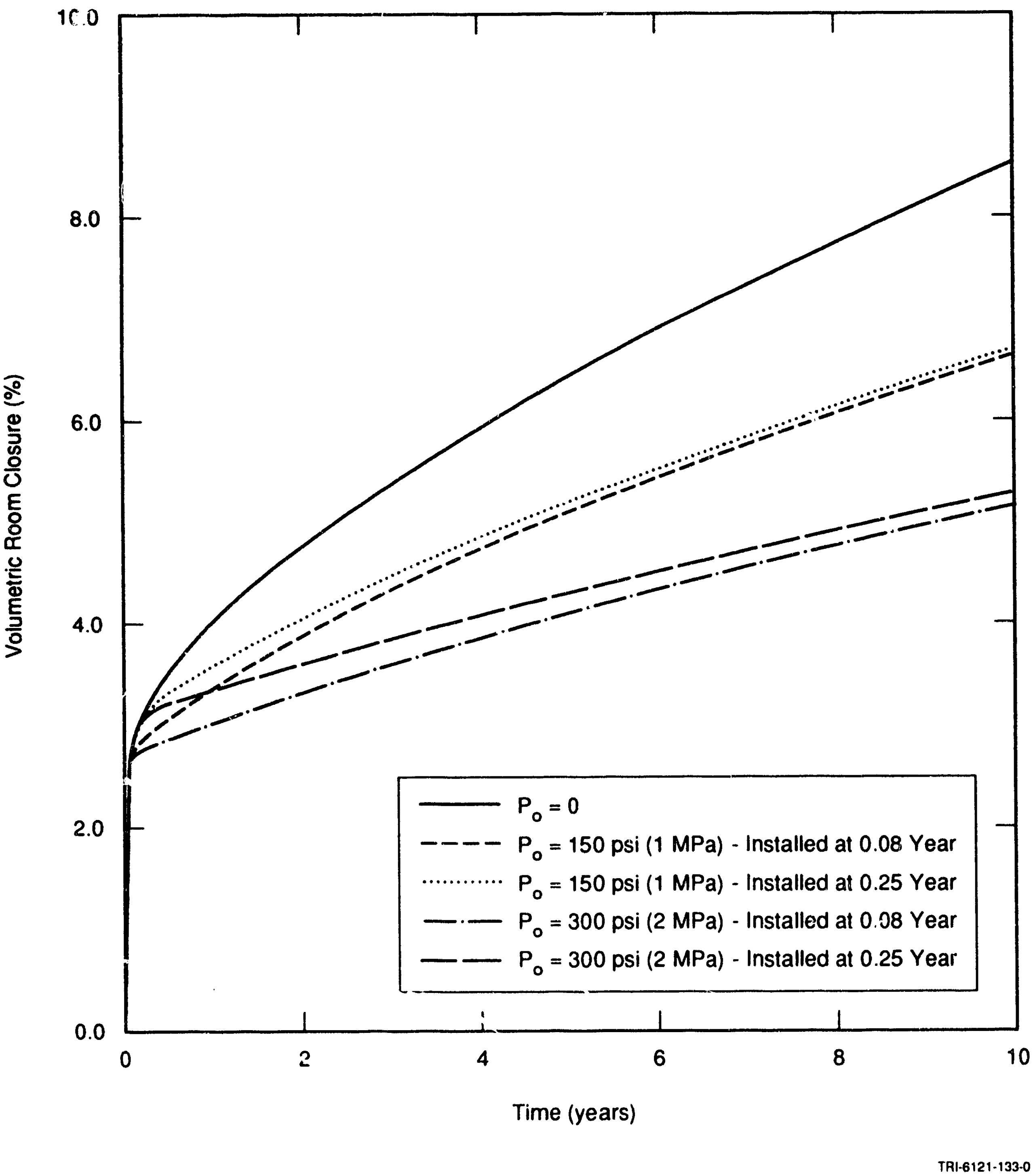

Figure 4-14. Volumetric room closure for circular cross-sectional drift with and without yielding seals.

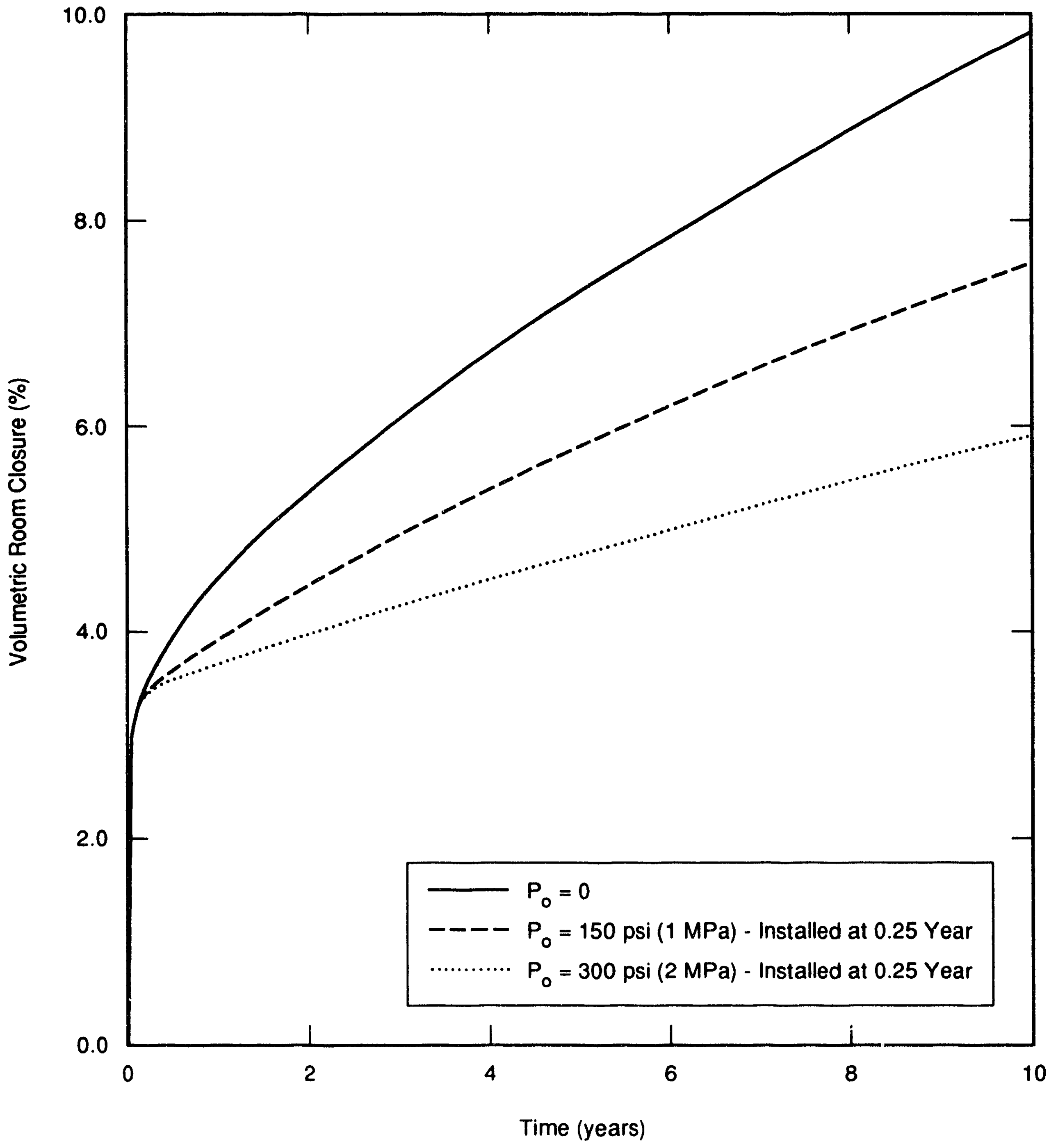

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Figure 4-15. Volumetric room closure for a rectangular cross-sectional drift with and without yielding seals.

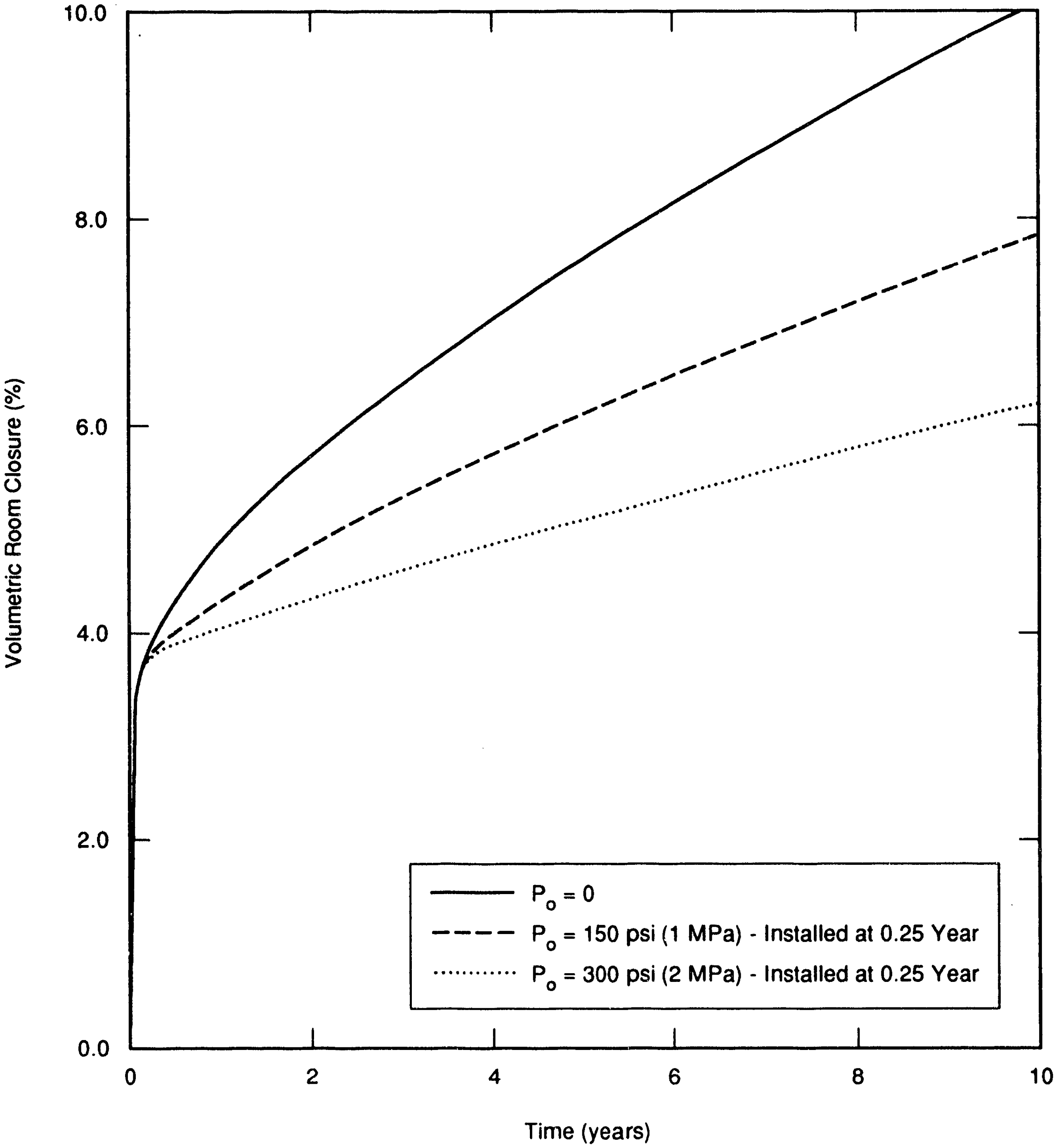

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Figure 4-16. Volumetric room closure for a horseshoe cross-sectional drift with and without yielding seals.

5.0 ROUGH ORDER-OF-MAGNITUDE DIFFERENTIAL COST ESTIMATE

A rough order-of-magnitude differential cost estimate that considers only the capital cost for procurement and erection of the seal structure was prepared. The costs for operational maintenance, remedial grout, monitoring, and operation of the monitoring system are not included. The cost for financing, engineering, construction management, instrumentation, testing, and so forth, was assumed common to all concepts and therefore was excluded from the differential cost estimate.

Tables 5-1 and 5-2 summarize the rough order-of-magnitude cost estimates in terms of first quarter 1993 dollars. The rigid sleeve concept (Concept 1) shows the highest initial cost of $456,000. The steel ring seal concept (Concept 4) with monitoring chamber shows the lowest initial cost of $105,000, including both rings but not the gas monitoring system. However, the steel ring concept is the most likely of all six concepts to require a monitoring chamber whose operation may cost many times more than the seal itself. The yielding sleeve concept (Concept 2) is the lowest cost of NOW concepts at $187,000, which is about one-third the cost of a rigid sleeve seal. The costs for the yielding sleeve concept do not reflect development and demonstration costs that would likely be high for this option. Initial costs of the two concrete monoliths are different because of additional excavation for Concept 6, and no accounting in Concept 5 for remedial grouting.

Table 5-1. Rough Order-of-Magnitude Cost Estimate
NOW Concepts for Operational Period Seal

			Concept 1		Concept 2		Concept 3	
		Emplaced	Rigid Sleeve		Yielding Sleeve		Ring with Inflated Tubes	
Item	Unit	Unit Price	Quantity	Cost	Quantity	Cost	Quantity	Cost
NOW								
Steel (100 ksi)	Ton	$10,000	37	$370,000	N/A	N/A	N/A	N/A
Steel (70 ksi)	Ton	$6,000	N/A	N/A	17.5	$105,000	25.4	$152,400
Precast Concrete	CY	$400	32	$12,800	N/A	N/A	N/A	N/A
Foam Concrete	CY	$1,000	N/A	N/A	37.4	$37,400	N/A	N/A
Cement-based Grout	CY	$1,500	16.5	$24,750	7.9	$11,850	N/A	N/A
Membrane	SF	$10	1139.4	$11,394	850	$8,500	N/A	N/A
Inflated Tube	LF	$250	N/A	N/A	N/A	N/A	393	$98,250
Excavation (Extra/Manual)	CY	$400	43	$17,200	10.3	$4,120	29.6	$11,840
Unit Cost (at the Time of Excavation)			1	$436,144	1	$166,870	1	$262,490
At the time of Panel Closure								
Steel-Plate Bulkhead (36 ksi)	Ton	$5,000	4	$20,000	4	$20,000	4	$20,000
Unit Cost (at the Time of Panel Closure)			1	$20,000	1	$20,000	1	$20,000
Total Unit Cost			1	$456,144	1	$186,870	1	$282,490

Note:

N/A: Not applicable

Table 5-2. Rough Order-of-Magnitude Cost Estimate
LATER Concepts for Operational Period Seal

			Concept 4 Steel Ring Seal with Monitoring Chamber		Concept 5 Concrete Monolith with Monitoring Chamber		Concept 6 Concrete Monolith with Excavation of MB139	
Item	Unit	Emplaced Unit Price	Quantity	Cost	Quantity	Cost	Quantity	Cost
Steel (70 ksi)	Ton	$6,000	6.2	$37,200	N/A	N/A	N/A	N/A
Steel-Plate Bulkhead (36 ksi)	Ton	$5,000	8	$40,000	N/A	N/A	N/A	N/A
C.I.P. Concrete	CY	$900	N/A	N/A	174.2	$156,780	178	$160,200
Membrane	SF	$10	N/A	N/A	N/A	N/A	925.4	$9,254
Inflated Tube	LF	$250	98.3	$24,575	104	$26,000	N/A	N/A
Remedial Grouting	1 Lot	TBD	1	TBD	1	TBD	N/A	N/A
Monitoring Chamber	1 Lot	TBD	1	TBD	1	TBD	N/A	N/A
Excavation (Extra/Manual or Shielded)	CY	$400	7.4	$2,960	5	$2,000	191	$76,400
Unit Cost			1	$104,735	1	$184,780	1	$254,854

Note:

N/A: Not applicable

TBD: To be determined based on full-scale tests

6.0 ADVANTAGES AND DISADVANTAGES OF DESIGN CONCEPTS

6.1 Concept 1 — Rigid Sleeve

Advantages

A1.1 A rigid sleeve can be designed using prevailing industrial codes and standards and can be installed within a 3-month period after excavation.

A1.2 The rigidity of the sleeve will control the DRZ and minimize deformation at MB139.

A1.3 The rigid sleeve can be made of precast elements fabricated in a shop to ensure quality control.

A1.4 A stiffened steel-plate bulkhead would be easy to place at the time of panel closure.

A1.5 The stiffened steel-plate bulkhead allows relatively easy access to the waste panel for potential monitoring.

A1.6 Rock bolt installation is not necessary.

A1.7 Grouting of MB139 may not be required.

Disadvantages

D1.1 Installation requires special equipment to handle and erect the heavy precast elements.

D1.2 The required thickness of the steel could present constructibility problems, and this structure may also require high-strength concrete.

D1.3 A rigid sleeve is a costly concept.

D1.4 Construction requires significant welding to be completed underground.

D1.5 Because this concept uses a round excavation, the passageway through the rigid sleeve may require ramping up and down with respect to the floor of the access drift and waste panel.

D1.6 This sleeve concept may increase costs for waste emplacement and panel development by requiring access through a narrower opening.

D1.7 The concept is not applicable to existing excavations.

6.2 Concept 2 — Yielding Sleeve

Advantages

A2.1 A yielding sleeve using available materials can be designed and constructed within about 1 month after excavation.

A2.2 The rigidity of the yielding sleeve is expected to heal the DRZ in salt and reduce deformation at MB139 below the seal.

A2.3 The liner loading is small; therefore, the required steel is easy to handle and erect.

A2.4 A stiffened steel-plate bulkhead would be easy to place at the time of panel closure.

A2.5 The stiffened steel-plate bulkhead allows relatively easy access to the waste panel for potential monitoring.

A2.6 The floor of the yielding sleeve can be flat and flush with the floor of the adjacent access drift, and the excavation equipment for the yielding sleeve is available at the WIPP.

A2.7 The yielding sleeve can be fitted into a large drift without significant constructibility problems.

A2.8 The capital cost is the lowest of the NOW concepts.

Disadvantages

D2.1 The damage to MB139 caused by creep deformation during the operational period is not predictable. The threshold deformation at MB139 that would cause leak passages from the waste panel needs to be identified by tests.

D2.2 Effective grouting material and procedures to repair damage to MB139 need to be developed.

D2.3 This concept may require more in situ demonstration to evaluate effectiveness than other concepts. The idea of DRZ mitigation by applying a nominal back stress via a yielding medium would likely require a convincing demonstration for Environmental Protection Agency or Mine Safety and Health Administration, for example.

D2.4 Development costs would likely be very high for this concept. Both performance and safety-related questions must be overcome.

D2.5 This concept does not eliminate further movement of MB139 and provides only minimal reduction in deformation.

D2.6 There are no prevailing industrial codes and standards for a yielding sleeve.

D2.7 This sleeve concept may increase costs for waste emplacement and panel development by requiring access through a narrower opening.

D2.8 The concept is not applicable in existing excavations.

6.3 Concept 3 — Steel Ring with Inflated Tubes

Advantages

A3.1 This sleeve concept can be designed and constructed using the prevailing industrial codes and standards within about 1 week after excavation.

A3.2 The back pressure from the yielding sleeve is expected to heal the DRZ in salt and reduce deformation at MB139 below the seal.

A3.3 The sleeve loading is small; therefore, the steel is thin and easy to handle and erect, like the yielding sleeve of Concept 2.

A3.4 A stiffened steel-plate bulkhead would be easy to fit at the time of panel closure.

A3.5 The stiffened steel-plate bulkhead allows relatively easy access to the waste panel for potential monitoring.

A3.6 The time of unsupported excavation can potentially be reduced to 1 week, which would reduce formation of the DRZ in the salt and the initial deformation of MB139.

A3.6 A defective seal ring can be removed and repaired, if required.

Disadvantages

D3.1 The damage to MB139 caused by creep deformation during the operational period is not predictable. The threshold deformation at MB139 that would cause leak passages from the waste panel needs to be identified by tests.

D3.2 Effective grouting material and procedures to repair damage to MB139 need to be developed.

D3.3 Installation requires a custom-made shearer for excavation of the ring groove. However, this disadvantage is expected to have little cost and schedule impact.

D3.4 The inflated tubes need to be monitored and maintained throughout the operational period.

D3.5 This sleeve concept may increase costs for waste emplacement and panel development by requiring access through a narrower opening.

D3.6 This concept does not eliminate further movement of MB139 and provides only minimal reduction in deformation.

D3.7 There is no previous experience for tubes of this size held at these pressures for such a long design life.

6.4 Concept 4 — Steel Ring Seals with Monitoring Chamber

Advantages

A4.1 Nothing needs to be built until the time of panel closure. Therefore, there is no initial cost and no impact on the panel development and waste emplacement.

A4.2 This seal concept is simple and can be installed in a short time with prefabricated components.

A4.3 This concept requires minimal space, which allows extra space for waste disposal, if needed.

Disadvantages

D4.1 Since the back pressure is applied to the DRZ after seal construction and only over a fairly small zone, the DRZ is not likely to heal.

D4.2 Of the six concepts, this seal system concept, is most likely to require a monitoring and maintenance system for processing and disposal of the leakage from the waste panel.

D4.3 The narrowness of these steel rings could give rise to stress concentrations (Figure 4-3) that would likely cause salt deterioration.

D4.4 No restraint is offered to continued development of the DRZ, which makes this concept the most likely to leak.

D4.5 This concept would likely require periodic grouting.

6.5 Concept 5 — Concrete Monoliths with Monitoring Chamber

Advantages

A5.1 Nothing needs to be built until the time of panel closure. Therefore, there is no initial cost and no impact on the panel development and waste emplacement.

A5.2 The rigidity of the concrete monolith will resist creep closure with significant back pressure to heal the DRZ in salt around the monoliths.

A5.3 The monolith has strength to withstand significant gas pressure.

A5.4 This type of seal does not require special equipment for excavation.

Disadvantages

D5.1 The concrete monolith may require high-strength concrete and reinforcement for tensile stress.

D5.2 The disturbance to MB139 will likely necessitate grouting.

D5.3 This concept may require use of impermeable membranes to make the concrete monolith gas-tight.

6.6 Concept 6 — Concrete Monolith with Excavation of MB139

Advantages

A6.1 Nothing needs to be built until the time of panel closure. Therefore, there is no initial cost and no impact on the panel development and waste emplacement.

A6.2 The rigidity of the concrete monolith will resist creep closure with significant back pressure to prevent development of the DRZ after emplacement.

A6.3 The monolith has strength to withstand significantl gas pressure.

A6.4 This concept is least likely to require grouting because MB139 is removed.

Disadvantages

D6.1 There is no assurance that all leak passages in MB139 and the DRZ around the monolith will be removed during excavation for the seal, or that the seal will be effective at the time of installation.

D6.2 The concrete monolith may require high-strength concrete and reinforcement for tensile stress.

D6.3 This concept may require special equipment for excavation.

D6.4 This concept may require use of impermeable membranes to make the concrete monolith gas-tight.

7.0 EVALUATION OF PROPOSED CONCEPTS

One of the fundamental issues regarding the sealing alternatives is whether significant technical advantages can be achieved by constructing some seal components in advance of panel development and waste emplacement. Therefore, concepts outlined in this report evaluate the significance of NOW options versus LATER options. If demonstrable technical advantage is achievable at a reasonable cost, the effort to install seals NOW would be warranted. If such advantage cannot be demonstrated, then sealing LATER would be most viable. Indeed, because many of the entries in the WIPP facility that must eventually be sealed already exist, assurance must be obtained that a LATER seal concept will be successful.

This section examines two of the six concepts in slightly more detail to provide arguments to be considered in future design. In particular, one potentially acceptable NOW concept using a yielding sleeve is compared with a favorable LATER concept using a concrete monolith as the key structural feature. This comparison may provide some guidance for the future sealing program.

The calculational results and other evidence provided earlier in this text are used to establish that *there is not a significant technical advantage to the NOW concept seals*. Although elements of the NOW concept seals could potentially meet the design requirements, it is recognized that the NOW concepts are generally more costly (Section 5) at the outset. The higher initial costs estimated in the text do not, however, reflect development, demonstration, or testing costs. It is probable that elements of the NOW concept seals would need demonstration and testing, as would elements of the LATER concepts. A significant difference in the amount of effort and risk for demonstration between the NOW and LATER concepts is perceived. The LATER seal concepts that use a concrete monolith more closely resemble current industry practice for bulkheads. It is therefore anticipated that high-quality concrete can be delivered and emplaced properly in the WIPP underground. An evaluation of the concrete emplacement and attendant functional measurements for the LATER concept are considered straightforward. The NOW concepts, on the other hand, would require more sophisticated field demonstration and testing of the concept itself. The advantage achieved by reduction of the DRZ would need to be convincing. Because the permeability properties of the DRZ have not been correlated to deformation, the yielding sleeve or the steel rings from the NOW concepts have an inherent and unknown risk.

It needs to be reiterated that these are only concepts. Upon further review, ideas emanating from these concepts may guide detailed design. In addition, the concepts forwarded in this section help identify several issues related to design and performance that might be resolved or better understood through field experiments and technology demonstrations.

7.1 Proposed NOW Seal Concept

The horseshoe-shaped yielding sleeve is proposed as a potentially viable NOW seal concept that could meet operational-period requirements. This concept was selected for the following reasons:

- Excavation of the horseshoe entryway can be completed using existing WIPP equipment.

- Installation would be straightforward because the yielding sleeve is relatively light and easy to handle. By contrast, installation of the rigid sleeve would be significantly more cumbersome.
- The opening shape and size are considered nonrestrictive in terms of access to the panel for waste emplacement.
- The initial cost is competitive with all concepts considered.

The yielding sleeve concept is not without some risk, and therefore would require in situ demonstrations to evaluate the perceived advantages. Cost for development and testing could be very high.

The yielding sleeve concepts offer two technical advantages compared to constructing nothing until panel closure. As discussed in Section 4, the yielding sleeve mitigates all of the DRZ in salt and reduces the deformation of MB139 by about one third. These two aspects may not be enough to justify a detailed design, considering that thirteen of the panel and drift seal locations have already been excavated and cannot take advantage of any of the benefits from NOW concepts. However, the calculated benefits are based on current capabilities to model structural responses at the WIPP. Our understanding of WIPP rock behavior is improving (i.e., through salt damage modeling and MB139 testing) and the benefits are not quantifiable at this time.

Figure 7-1 shows a horseshoe-shaped yielding sleeve seal concept. At the time of access excavation (Phase 1 in Figure 7-1) the yielding sleeve is installed. At the time of panel closure (Phase 2 in Figure 7-1), a stiffened steel-plate bulkhead is placed at the waste panel end. By itself the steel-plate separation between the waste room and the mine allows ready access for monitoring. The effectiveness of the seal could be evaluated by instrumentation inside the waste panel. Possible seeded-gas leakage tests at MB139 and clay seams F and G could be planned and executed. Remedial grouting through the yielding sleeve is also possible.

If there are any indications of unacceptable leakage, this concept facilitates construction of a monitoring chamber that could be built by installing a single steel ring seal in the entry (shown as Phase 3 in Figure 7-1). The air inside the chamber would be maintained at a slight negative pressure, which would allow effective monitoring.

7.2 Proposed LATER Seal Concept

The familiar concept of a large concrete monolith potentially coupled with a ring-and-tube bulkhead to create a monitoring chamber is recommended for further development. The LATER concept proposed for additional study is illustrated in Figure 7-2. This concept features several positive attributes. The first obvious advantage of this concept for the general sealing program is that nothing special needs to be built now for preparation. Emplacement of panel and drift seals can be postponed until needed. When the seal is installed, both MB139 and a nominal depth of the salt DRZ will be excavated. Thus, the total disturbed zone will be replaced with an engineered material, namely concrete, with particular design considerations to mediate permeability. Removal of the total DRZ could obviate the need for remedial grouting.

A simple monitoring chamber could be created in this conceptual seal strategy if any leakage is detected, or if monitoring is required for other reasons. A steel ring with an inflated tube would form a bulkhead at an appropriate distance down the entry. A slight negative pressure could be applied to the chamber, and monitoring for VOCs could be easily incorporated.

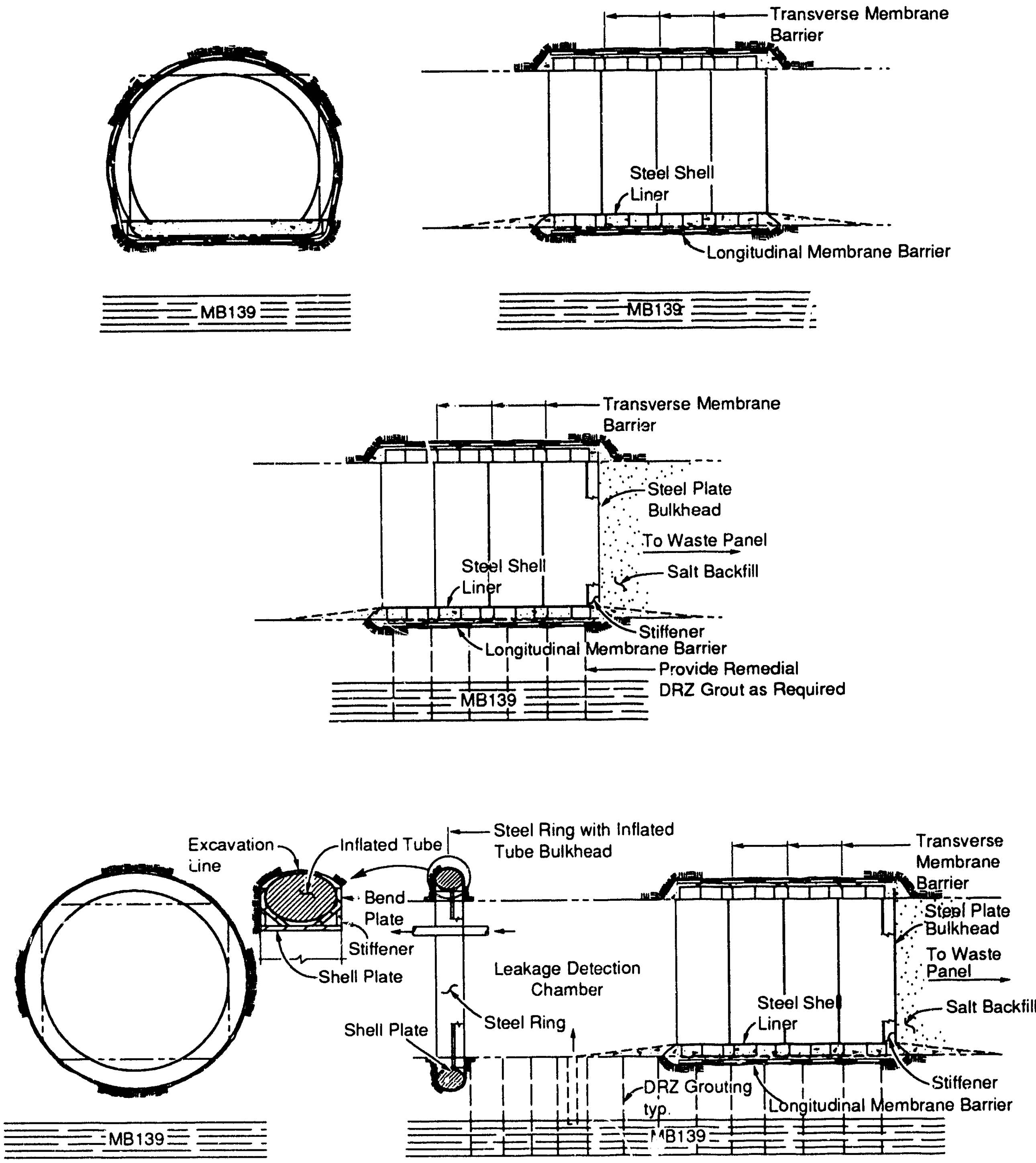

Figure 7-1. Proposed NOW concept for operational period seal.

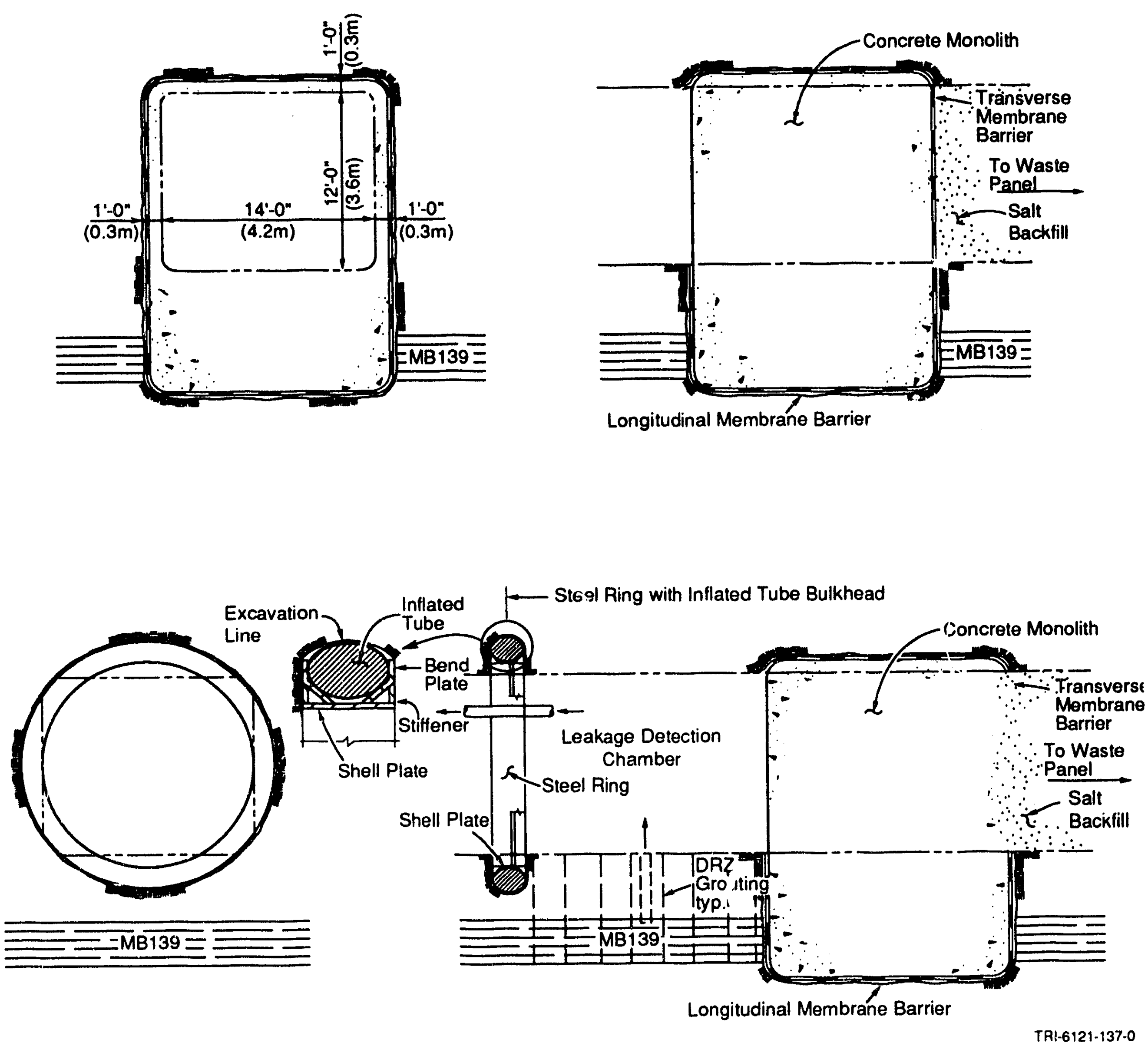

Figure 7-2. Proposed LATER concept for operational period seal.

There is not a large difference between LATER concepts that utilize concrete monoliths. Concept 5 places the concrete in an existing opening without excavation of the DRZ. Concept 6 places the concrete after excavation of the salt DRZ and MB139. It is expected that grouting would be required if the DRZ and MB139 are not removed, whereas grouting may not be necessary if they are removed. This tradeoff of grouting versus excavation results in the cost estimate differential (Table 5-2) because cost of excavation is included, and cost of remedial grouting is excluded. The technical arguments about whether it would be more effective to reduce gas permeability by removing the DRZ or by grouting remain unresolved as of this writing.

8.0 RECOMMENDATIONS

This study has presented the feasibility of NOW or LATER seals for operational period requirements. The seal design from this point forward is an iterative process of construction, performance monitoring, and remedial actions to meet EPA requirements. The potential for successful seal design could be greatly enhanced if some supporting experiments and verification of the in situ characteristics are conducted. These tests and verifications will not only evaluate some technical assumptions, but they will also allow WIPP site personnel to establish effective procedures for emplacement. Demonstrations of the ability to emplace certain elements of the design (such as placement of a large-volume, high-performance concrete and evaluation of the leak rate through the DRZ around the seal) are crucial to establish the credibility of the concepts. Performance evaluation of the concepts also underpins acceptance of the seals and, hence, provides objective input to the decommissioning plan.

If implemented, elements of the recommendations in this section could be integrated into the early stages of the Large-Scale Seal Test program. The proposed demonstrations and associated measurements include aspects of large-volume concrete emplacement and measurement of permeability through the DRZ along the concrete-salt interface and through the concrete. Several variations of the concrete emplacement are discussed in Section 8.1. The concrete emplacements could be instrumented to help validate code calculations and determine design specifications. And finally, characterization of rigid-plastic materials may help confirm the viability of the yielding sleeve concept.

8.1 Cast-in-Place Concrete

Although concrete has been emplaced in large volumes in many mining situations deep underground, it is important to demonstrate that concrete can be delivered and emplaced in the WIPP underground properly to meet the requirements of the sealing program. Because the sealing system must meet strict performance requirements in a first-of-its-kind facility, strong assurance of success is critical. The present mining practices and measurements of concrete performance in situ do not establish sufficient confidence that design requirements for the operational period at the WIPP can be met. A large-volume casting of concrete at the WIPP site would not only evaluate the technology, it would offer an opportunity to make a series of measurements to provide information for design of the LATER seal concept. Concrete emplacement might include both freshwater formulations and salt-saturated formulations as follows.

8.1.1 Salt-Saturated Concrete

A long-standing research program at the Waterways Experiment Station has led to a recommendation for a salt-saturated mass concrete to be used in seals at the WIPP (Wakeley et al., 1993). The ability to place large volumes of a particular salt-saturated concrete has not been demonstrated, particularly within the infrastructure and rigorously controlled environment at the WIPP site. A demonstration of the ability to place a large volume of salt-saturated concrete and obtain acceptable performance characteristics of the concrete for periods up to 35 years is fundamental to the sealing program.

8.1.2 Freshwater Concrete

Freshwater Portland cement concrete is a desirable material from a construction viewpoint because it is a standard construction material that has been well proven by the concrete industry, particularly when high performance is concerned. The problem with use of freshwater concrete at the WIPP concerns free water that would dissolve salt at the interface and potentially create a preferred pathway for gas leakage. One engineering solution to this problem, as recommended here, is to place a membrane or other impermeable material between the concrete and the salt. In this way, dissolution is prevented initially and brine access and chemical attack on the concrete may well be prevented entirely. Tunnel construction frequently involves the use of such an impermeable liner situated between the concrete and the host rock to prevent water infiltration. Although the perceived function of the liner is different in this application, the construction is common practice.

8.2 Permeability Evaluation

Each of the large-volume concrete placements, whether freshwater or salt-saturated, could be tested for permeability in its full-size functional setting. Figure 8-1 is a conceptual arrangement for such concrete placement using a membrane. The overall concept could be identical for salt-saturated concrete, but without a membrane. To facilitate permeability testing, a small room would be sealed by the concrete monolith. Access to the room behind the monolith for purposes of pressurization or seeding tracer gas could be attained either through the monolith itself (as shown in Figure 8-1), through a barrier pillar, or from a parallel drift. The seeding, pressurization, and testing process will be developed at a later stage concurrent with designs and specifications.

Although the demonstration of the concrete placement and associated structural, physical, and mechanical measurements on the concrete itself are important to seal system design, the measurement of permeability is crucial to determine performance for meeting regulations. Therefore, in situ permeability testing needs to be considered which includes:

- Use of an "old" unmodified drift. An evaluation of permeability through the DRZ, interbeds, and deformed MB139 would be possible by using a disturbed opening.
- Excavation of MB139 and removal of the DRZ. An excavation of this nature would be required to implement the concept shown earlier in Figure 7-2. Such an emplacement of concrete would include as a prerequisite an assessment of excavation techniques.
- Remedial grouting could be used in conjunction with any of the concrete placements and permeability tests.

8.3 Load History of the Rigid Monoliths

During the concrete emplacements, pressure gauges, temperature gauges, and strain gauges may be installed for monitoring creep-closure loading, strain, and temperature. The measured interface pressure may be used to validate the value predicted by rock mechanics analysis. The load measured in this type of test is important

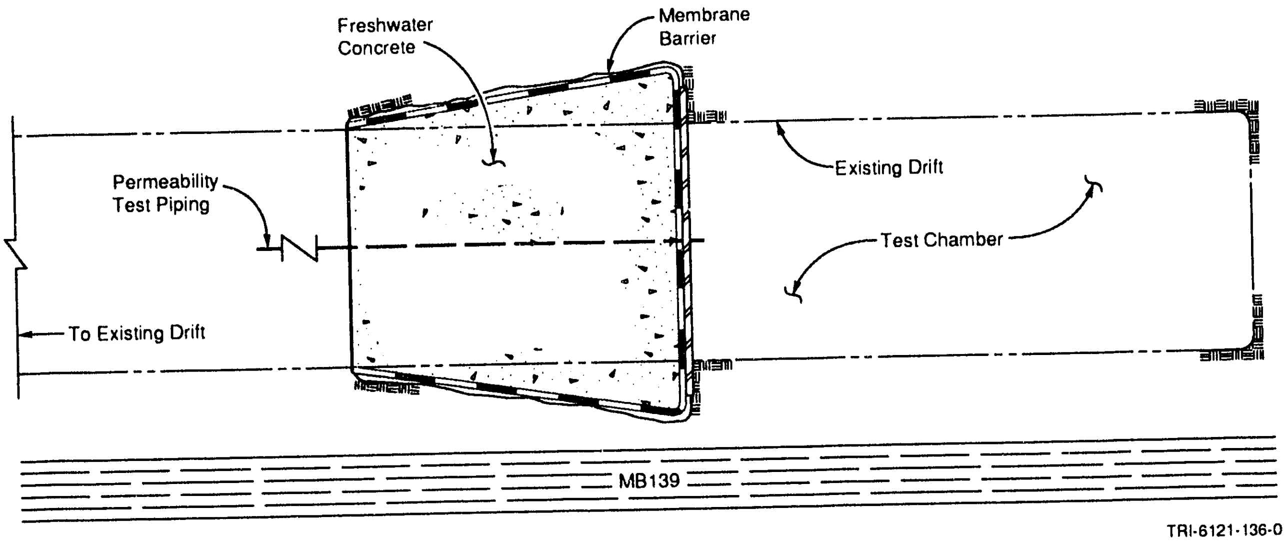

Figure 8-1. Permeability test for a freshwater concrete monolith.

for design validation. The design is based on structural analyses (rock mechanics), and measurement of load or pressure will help validate important design assumptions. Also, tensile stress in conjunction with high compressive stresses resulting from salt creep at the interface could develop in the rigid monolith. Remediation may require use of reinforcement in the concrete monolith design

8.4 Candidate Materials for Yielding Sleeves

The results of the rock mechanics analysis in Section 4 showed that the yielding sleeve concept may reduce the total DRZ and promote healing of the DRZ in salt with 300 psi (2 MPa) or less loading. A preliminary estimate showed that the initial cost of a yielding sleeve is about one-third that of a rigid sleeve and that there could be a significant reduction in the construction schedule. A yielding sleeve concept may be a potentially viable solution, but requires further evaluation of two aspects in particular: (1) materials for rigid-plastic design, and (2) assessment of effectiveness of DRZ control and permeability reduction. Although honeycomb materials developed for the aerospace industry can be used to provide the required rigid-plastic characteristics of a yielding sleeve, their cost is probably prohibitive. Industrial materials such as lightweight foam concrete and construction chemicals seem to have the required rigid-plastic characteristics. However, these materials are mainly marketed for insulation, water cutoff, and soil stabilization and not for structural purposes as conceived here. Therefore, rigid-plastic materials need to be identified, tested, and documented for their mechanical properties and chemical stability in the WIPP environment before they can be demonstrated in an underground situation or used in detailed design.

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Nuclear Waste Technical Review Board (2)
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Environmental Evaluation Group (3)
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NM Bureau of Mines and Mineral Resources
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NM Energy, Minerals, and Natural Resources Department
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NM Environment Department (3)
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NM Environment Department
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Battelle Blvd.
Richland, WA 99352

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6850 Austin Center Blvd.
Suite 300
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INTERA Inc.
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Los Alamos National Laboratory
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Seattle, WA 98195

Libraries

Thomas Brannigan Library
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Las Cruces, NM 88001

Government Publications Department
Zimmerman Library
University of New Mexico
Albuquerque, NM 87131

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Hobbs, NM 88240

New Mexico State Library
Attn: N. McCallan
325 Don Gaspar
Santa Fe, NM 87503

New Mexico Tech
Martin Speere Memorial Library
Campus Street
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WIPP Public Reading Room
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