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INFORMATION BASE FOR WASTE REPOSITORY DESIGN

Volume 5
Decommissioning of Underground Facilities

Michael S. Giuffre Charles M. Koplik
Robert L. Plum Richard Talbot

The Analytic Sciences Corporation

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The Analytic Sciences Corporation
6 Jacob Way
Reading, MA 01867

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FOREWORD

This report is Volume 5 of a seven volume document on nuclear waste repository design issues. A large portion of the work reported in this document was performed by Golder Associates, Inc. under a subcontract to TASC. Principle Golder authors of this report are Robert L. Plum and Richard Talbot. The authors would like to thank Michael Kearney and William M. Grayson of NRC for their encouragement and assistance.

1847 333

ABSTRACT

This report discusses the requirements for decommissioning a deep underground facility for the disposal of radioactive waste. The techniques for sealing the mined excavations are presented and an information base on potential backfill materials is provided. Possible requirements for monitoring the site are discussed. The performance requirements for backfill materials are outlined. The advantages and disadvantages of each sealing method are stated.

1847 334

TABLE OF CONTENTS

1847 335

TABLE OF CONTENTS (Continued)

1847 336

LIST OF FIGURES

1847 337

LIST OF FIGURES (Continued)

LIST OF TABLES

1847 338

1. INTRODUCTION

At the completion of the disposal operations in an underground nuclear waste repository, the facility will be decommissioned. Decommissioning includes all activities required to close the repository and observe its performance. This could include backfilling the depository, sealing the shafts, erection of permament surface markers, dismantling the surface facilities and long-term instrumentation and monitoring. The purpose of this volume is to evaluate the performance of techniques for decommissioning the repository to ensure long-term containment and to minimize risk of release of radioactive material. Erection of surface markers and dismantling of surface facilities is, however, beyond the scope of work and will not be discussed in this report.

1.1 OVERVIEW

A description of the available techniques for placing backfill in a repository (hydraulic, pneumatic, mechanical, etc.) is given and the potential advantages and disadvantages of each described. The method used will influence the ultimate effectiveness of the emplaced material and should be chosen with some care.

An information base is then provided on the properties of backfill material. The merits of each material are assessed on the basis of what are considered the desirable qualities of a backfill material. This data base can be used to evaluate decommissioning methods that are proposed for nuclear waste repositories.

1847 339

Performance requirements are discussed for the backfilled depository. These include structural, hydrologic, chemical, and economic considerations. Where appropriate, recommended values of backfill properties are provided.

Shaft sealing including both sealing and shaft opening and any associated fracture zones around the opening are key elements of any decommissioning operation. Both of these topics are covered in detail in Volume 1 and are not discussed here.

1.2 DECOMMISSIONING OBJECTIVES

The primary objectives for decommissioning the repository may include:

- Minimizing the risk of intrusion by man
- Maximizing the natural long-term confinement of the waste
- Monitoring the long-term performance of the repository.

To satisfy these requirements, perfect decommissioning would consist of backfilling all underground openings with a material which exactly matched the strength and deformation characteristics of the host rock. In addition, the backfill would have a low permeability, be noncorrosive, insoluble, and exhibit high nuclide retardation/adsorption behavior. Monitoring and surface markers might be installed and would be functional for as long as deemed necessary.

Perfect decommissioning is not feasible technically nor economically; however, perfect decommissioning may not be necessary to provide adequate waste isolation for properly chosen sites and repository designs. Thus, the intent of the decommissioning performance requirements should be to define a procedure which is both realistic and consistent with the needs of the specific repository design/environment. It is not possible to precisely define these needs until long-term risk analyses are completed and a specific site and design are chosen.

In brief, the important qualities of the depository backfill material include:

- Permeability: Theoretically, it is not necessary to have a backfill with a low permeability in an unflawed depository with an impermeable shaft seal. However, should the shaft seal fail or the depository be breached by flaws (faults, breccia pipes, failed borehole seals, etc.), a low permeability backfill will minimize negative impacts. Based on preliminary results from long-term risk models, backfill permeability less than 10^{-5} cm/sec is desirable.

- Porosity: The porosity of the backfill will affect the time required for the depository to resaturate with water following decommissioning. In general waste will not escape from the depository until resaturation occurs. The higher the porosity of the backfill, the longer the potential resaturation time. It should be noted, however, that a low porosity may be desired to reduce the quantity of water which could potentially contact the waste.

- Strength and Rigidity: Deformations above the depository could lead to extensive fracturing around the openings, distortion and cracking of overlying formations, and surface subsidence. The backfill can minimize or eliminate these problems. The more rigid the backfill (in relation to the host rock), the greater its structural benefit.

1847 341

- Retardation Behavior: Backfill materials which retard or adsorb radionuclides will provide an additional barrier to radionuclide transport.

- Chemical Properties: An ideal backfill should not adversely react with the waste and should not dissolve in groundwater.

- Durability: The backfill should not deteriorate for hundreds or thousands of years.

- Thermal Properties: The backfill should be stable at the anticipated elevated temperature caused by the waste canister heat.

A proper evaluation should not consider these properties separately but must consider the entire system consisting of the backfill, depository design, shaft seals, geologic and hydrologic environment, etc.

1.3 ORGANIZATION OF THE REPORT

Chapter 2 describes and evaluates backfilling techniques. An information base on backfill materials is provided in Chapter 3. A brief description of monitoring and instrumentation is given in Chapter 4. Performance requirements for backfill are described in Chapter 5. Conclusions on potential decommission schemes and recommendations for future work are given in Chapter 6. Appendix A presents the results of post-decommissioning thermal analysis. A glossary of important technical terms appears at the end of this report.

1847 342

2. BACKFILLING TECHNIQUES

2.1 CURRENT MINING PRACTICES

2.1.1 Introduction

Unless there is an economic, safety or legal reason, mine openings are not normally backfilled. Abandonment might consist simply of covering or fencing the mine entrances. Reasons for backfilling include:

- To limit surface subsidence in areas overlain by surface structures. A common practice in populated coal mining areas.
- As structural support in cut and fill mining. Also used to fill stopes and allow for the pillar to be mined.
- For disposal of mine waste to minimize surface impact and/or handling costs.
- To seal off sections of the mine.

The common types of backfill techniques discussed below are hydraulic, pneumatic, and mechanical. An execllent reference of mine backfilling is the proceedings of the "Jubilee Symposium on Mine Filling, Mount Isa, August 1973" sponsored by the Australian Institute of Mining and Metallurgy.

2.1.2 Hydraulic Backfilling

The history of hydraulic filling of mines goes back to about 1864, according to Lightfoot (Ref. 1), where filling

1847 343

was used to control subsidence under a church. Subsequently it has been used to extinguish underground coal fires. The idea spread rapidly, and af'er World War II it became standard practice at many mines throughout the world. Stabilization of fill by the addition of Portland cement or other suitable material was in common use by the mid-1960's. Modern hydraulic filling techniques have contributed significantly to more efficient mining by making possible new mining methods and extensive modification and mechanization of existing methods (Ref. 2).

Today hydraulic backfilling is the most common method used in the mining industry. It generally consists of mixing mine tailings or alluvium with water to form a slurry containing about 50 to 70 percent solids by weight. The slurry is pumped to the disposal area in wear-resistant pipes and flooded into the area to be filled. The excess water percolates through the fill and is pumped out of the mine. The resultant backfill is generally a clean sand material with a porosity of about 20 to 40 percent. Vibrator compaction is sometimes used to increase fill densities.

There are two basic placement methods used in hydraulic filling. These are:

- <u>Normal Filling from Within the Mine</u>: This is generally practiced in steeply dipping open stoping metal mines. In these mines, the vertical extent of the stopes is large compared to the horizontal extent. Bulkheads, usually consisting of timber cribbing or concrete, are used to seal off the openings to the stope. Then fill is pumped in from the top with excess water draining through the bulkheads or other drainage provisions. Due to the general geometry of the stope, fill segregation, bulkhead requirements, and unfilled void spaces against the roof are all minimal. Conversely, use of this method in horizontally extensive openings in room and pillar mines is normally not appropriate due to extensive bulkhead requirements, segregation problems, and difficulty in completely filling the openings.

- Filling from the Surface: Hydraulic fill can also be pumped into the mine openings through boreholes. This method has been used in shallow, relatively flat-lying abandoned coal mines to reduce subsidence problems (Ref. 3). As fill is pumped through a borehole, it builds up a cone of fill and eventually seals the hole from further injection. This method results in considerable segregation of material with coarser sizes concentrated near the boreholes and finer sizes between holes and/or in settling ponds created by drainage of the water into low areas of the mine. Generally a close spacing of boreholes on the order of 50 feet is used. Even at a close spacing, void undoubtedly exists between the boreholes. It has been found that better results can be obtained by creating a sealed injection pipe in the borehole and pumping under pressure. By pressure injection, tens of times as much fill can be placed from each borehole (Ref. 4), as compared to gravity feed methods. The filling ratio is also found to be higher because tabular rather than conical fills are created (Refs. 3 and 5).

As related to a nuclear waste depository, the primary advantage of hydraulic backfilling is that it is both economical and a well-developed technique. It also presents the option of using additives such as cement, to increase fill strength. However, there are several disadvantages which make it a poor candidate for depository backfilling. These disadvantages include:

1847 345

- Shrinkage: Hydraulically placed fill will shrink as the water drains and may produce a void between the fill and the depository roof.

- Permeability: Material suitable for hydraulic filling must drain and therefore would have a high permeability.

- Drainage Water: The excess water which drains from the fill introduces large quantities of unwanted water into the depository. Unless brines were used, the water could lead to severe solutioning in a salt repository.

- Placement Problems: As discussed above, there are inherent problems in effectively placing hydraulic fill in a horizontally extensive mine such as the current repository design concepts. Fill placement through boreholes would be unacceptable due to the depth of the depository, large number of holes required, and inability to fill all the voids.

- Saturated Fill Condition: Although excess water would be drained, the fill would still maintain a high water content close to saturation. Thus the unsaturated porosity would be very low. This would significantly reduce the time required to resaturate the depository.

- Low Strength: Hydraulic fill generally has a relatively low density and will often compress up to 20 percent of its initial volume under small loads. Portland cement can be added to improve the strength of the fill.

Concrete is a very special case of hydraulic fill and is discussed separately in Section 3.3.2. Many of the disadvantages discussed above do not pertain to concrete.

1847 346

2.1.3 Pneumatic Backfill

Pneumatic backfilling or stowing was developed in Germany in 1924 and spread throughout Europe attaining a peak in the fifties and early sixties. Recently pneumatic stowing usage has steadily declined due to high cost as well as dust and noise problems. In western Europe, at the present time, pneumatic stowing is being used exclusively in conjuction with longwall mining. Pneumatic stowing has had limited use in North America although it is currently being used by Cominco in British Columbia, by Kerr-McGee in Grants, New Mexico, by Ranchers Inc. in Mammath, Arizona, and has been tested by the U.S. Bureau of Mines in Spokane, Washington (Refs. 6, 8, and 9).

In essence, pneumatic stowing consists of placing fill with a high velocity air stream. The stowing material is generally crushed to pieces less than three inches in size and transported to the stowing or blower unit by conveyor belts, under gravity down rock passes, by mine cars, or by other feasible means. Compressed air is either piped to the stowing machine from the surface or generated underground close to the stower. Air and fill are mixed in the stowing machine and the mixture is ejected at high velocity from the machine through a short section of blowpipe. Once beyond the blowpipe the largest particles tend to fall short, but roll the farthest. Particles in the one-inch range tend to be thrown the farthest with small particles down to dust size losing velocity rapidly and settling without rolling. The particles impact the area to be filled, are lodged there, and build up a pack. A typical stower might develop an air flow rate of some 3000 cfm and spray particles at 60 mph at distances up to 100 to 200 feet. (Refs. 8 and 9).

1847 347

The primary advantages of pneumatic stowing are that large amounts of water are not used, a broader range of fill particle sizes can be placed, in flat-lying openings the fill can be placed tighter against walls and roofs, and it can result in a higher fill density. The primary disadvantages include high capital and operations costs as well as noise and dust problems. In addition, the passage of high-velocity stony material through steel pipe generates considerable static electricity and resultant sparks could be a fire hazard.

As related to nuclear depositories, pneumatic stowing has several advantages over hydraulic backfilling including:

- Dry Placement: Although some moisture may be added at the nozzle to control dust, pneumatic stowing is essentially a dry placement procedure without the shrinkage, drainage water, and saturated fill problems associated with hydraulic fill.
- Placement Conditions: Pneumatic stowing could be conveniently used in the types of depository geometries being currently considered.
- Close Packing: It would be possible to achieve close packing against the roof of the openings.
- Wider Range of Material: A wide range of materials could be placed. These might include coarse fill, crushed salt or dry bentonite balls.
- Higher Density: Under proper conditions, pneumatic stowing produces a denser fill. However, this increase in density is probably not sufficient to significantly alter its support behavior (see Section 5.2).

1847 348

The major disadvantage of pneumatic stowing is the high permeability of the backfill. To be effectively placed, the fill must be an aggregate of dry particles which can be transported by high velocity air. Such a material will inherently have a high in-situ permeability. Swelling materials with low permeabilities such as bentonite could be placed in a dry condition. Should water contact the fill, these materials would swell and produce a fill with a low permeability. Cost and operational problems are also a disadvantage but would not be as restrictive as in commercial mining ventures.

2.1.4 Mechanically Placed Fill

The conventional surface placement techniques used on civil construction projects involves dumping, spreading in thin layers and mechanically compacting fill to specified densities. Although placement of fill with mine cars, front-end loaders and/or conveyor belts is common, placement of controlled mechanically compacted fill is not done in underground mining. This is because of the high cost of such methods and the obvious space restrictions.

As related to nuclear depositories, the advantages of mechanical backfilling include:

- Moisture Control: Provided the material is not excessively wet, the fill can be placed under virtually any desired moisture condition.
- Range of Material: Virtually any type of fill can be placed. Combinations of materials including zonal placement can also be readily placed. Additives such as cements can be readily utilized.

1847 549

- Permeability: Since there is virtually no restriction on material type by this method of placement, low permeability fills such as compacted clays can be used.

- Density: High density can be obtained, although without cement additives any compacted fill would still be relatively weak compared to most rock types.

- Fill Control: Mechanical placement offers a high degree of control unavailable in either hydraulic or pneumatic fills.

The obvious disadvantages of mechanically placed fill relate to high costs and severe space limitation problems. Although some use of large compactors might be possible, extensive use of small compactors would probably be necessary. Procedures for placing and compacting fill against the roof could be worked out, but would undoubtedly be very tedious.

2.2 CURRENT NUCLEAR REPOSITORY CONCEPTS

2.2.1 Introduction

A review was made of the backfill techniques being developed for the various conceptual designs appearing in the available literature. The review incorporates only published information. It is not the intent of this section to judge the backfill concepts but rather to simply summarize them.

2.2.2 Crushed Salt Backfill

All of the design concepts in bedded salt developed by the Department of Energy (DOE) propose a crushed salt backfill (Refs. 10 through 12). Specific details on the placement of the salt backfill are lacking, but would probably consist of simple

1847 350

mechanical dumping without compaction. Based on unpublished information including discussions with Sandia personnel, DOE believes that the salt will creep and eventually fuse into a solid mass with characteristics similar to the surrounding natural bedded salt. Published information on crushed salt to support this behavior was not found (see Section 3.2.2).

There is a major economic and environmental advantage in using the native excavated salt for backfill. The costs of obtaining, transporting and placing millions of tons of selected backfill would be substantial. In addition, there would be major costs and potential environmental problems related to the surface storage of millions of tons of salt waste.

The general relevant properties of crushed salt backfill are discussed in Section 3.2.2. In essence, it appears that crushed salt would be a relatively compressible, highly permeable, and soluble backfill. The major uncertainty relates to the concept that the salt will fuse into a solid mass.

2.2.3 Sand-Bentonite Mixture

The Nuclear Fuel Safety Project (KBS), which was organized by the power industry in Sweden, has completed a conceptual repository design in crystalline rock (Ref. 13). The primary intent of the design was to demonstrate that the nuclear waste problem could be solved in a completely safe way.

The backfill proposed is a mixture of quartz-sand and bentonite. Bentonite is a swelling clay which has high retardation behavior and low permeability. Placed in an initially

1847 351

dry environment, bentonite will absorb any free water and swell. The mixtures being considered vary from 10 percent bentonite and 90 percent quartz sand to 20 percent bentonite and 80 percent quartz sand. The lower part of the backfill would be placed with conventional mechanical techniques in thin lifts and compacted. The upper fill up to the roof would be placed pneumatically.

2.2.4 Other Currently Envisioned Concepts

Numerous other design concepts exist but have not been developed sufficiently to delineate the specific backfill technique. There appear to be three general backfill concepts:

- Excavated Material: As discussed in Section 2.2.2, there are economic and environmental reasons to use the native excavated rock for backfill. The primary disadvantage in hard rock depositories (such as basalt and granite) would probably be the high permeability of the backfill. Proper placement of a crushed shale backfill could result in a relatively low permeability. These materials as well as crushed salt are discussed in more detail in Section 3.2.

- Sand and Clay Mixtures: A mixture of sand and clay such as proposed by the Swedes appears to provide an optimum combination of low permeability, high retardation, availability, chemical stability, and ease of placement. Probably the primary disadvantage of the backfill would be its relatively low strength and rigidity, and cost.

- Plugs: As a separate concept or in conjunction with backfilling, consideration is also being given to constructing impermeable plugs at strategic locations, such as the entrances to all the storage

1847 352

rooms. These plugs could be constructed of various materials, although concrete appears to be the likely candidate. The overall result would be to provide a system with low effective permeability longitudinal to the depository. Plugs are discussed in more detail in Volume 1.

2.3 OTHER POTENTIAL BACKFILL TECHNIQUES

There are several backfill techniques not used by the mining industry nor currently proposed in conceptual designs which may represent viable alternatives. These include:

- Concrete, Cement Grout, or Chemical Grout (Special Case of Hydraulic Fill): Theoretically, the entire deposit could be filled with concrete, cement grout or chemical grout. Their properties could be controlled to provide low permeability and high strength. The obvious disadvantage is the cost, which would probably be prohibitive.

- Natural Caving: Under proper conditions, natural caving and/or creep would close the depository openings and, in effect, provide a backfill. The obvious disadvantages include the lack of control and large deformations that result.

- Liquids: Filling the depository with a liquid which is immiscible with water and viscous enough to have a very low permeability in the native rock has several advantages. It could significantly increase the groundwater resaturation time and reduce or even eliminate water transport of the nuclides. This concept may decrease the deterioration of the waste by providing an inert environment.

1847 353

2.4 SUMMARY

This chapter describes the state of the art in backfill techniques currently employed in mines. This includes hydraulic backfill, pneumatic backfill, and mechanically placed backfill. None of these techniques appears to completely meet the objectives discussed in Chapter 1. Pneumatic stowing where a swelling material such as bentonite is added to the broken rock aggregate or mechanically placed backfill appear to be promising methods for backfilling a depository.

The conceptual designs available for bedded salt and granite indicate that both mechanical and pneumatic techniques are being considered. In the case of salt there is no evidence that crushed salt will readily fuse to a solid mass; under the conditions anticipated in the depository substantial time and deformation of the surrounding rock mass would be required. The laboratory data has only considered the short-term thermo-mechanical behavior of salt.

A mixture of sand and bentonite suggested for a granite depository offers high retardation and low permeability. The use of concrete or chemical grouts is a viable but expensive alternative. The use of liquids which are immiscible with water is an alternate concept which appears to merit further consideration.

3. PROPERTIES OF POTENTIAL BACKFILL MATERIALS

3.1 INTRODUCTION

This chapter provides a general data base of backfill material properties. For each potential backfill type data on pertinent properties are presented and discussed in relation to depository backfill requirements. In general, the properties discussed include permeability, porosity, mechanical behavior, nuclide retardation behavior, chemical stability, availability or cost, and placement requirements. General preliminary comments on the suitability of each backfill are also presented.

3.2 EXCAVATED MATERIAL

3.2.1 Introduction

For a bedded salt repository, economically and environmentally the obvious backfill material to use is the native excavated rock. Thus, there will be a strong incentive for DOE to develop a backfilling technique using the excavated rock. Based on current DOE site suitability concepts, the latter could be salt, shale, basalt, or granite.

The general gradation of the crushed rock backfill can be controlled with appropriate crushers, screens and mills. In general, eight- to ten-inch gradation can be readily obtained with conventional jaw or gyratory crushers underground. This is common practice in mines in order to transport the ore to the surface. Finer material down to about 1/4 to 1 inch size could also be obtained underground with additional screens and crushers. To obtain finer gradations, a major milling operation such an an autogenous, ball, or rod mills would be necessary. These installations are large and would probably require surface operation.

In general, the mechanical behavior, porosity, and permeability of an inert crushed rock backfill will depend on its gradation and compacted density. The finer and denser the fill, the lower the permeability will be. The denser, coarser and better-graded the fill, the stiffer it will be. The porosity of the fill can be adjusted by controlling the proportion of fine to dense fill.

The permeability of the fill will be controlled predominantly by the size of the finer portions of the grain size distribution. Density and uniformity will have lesser effects. As a rough guideline, permeability can be estimated from the empirical relation:

$$K = 100\ (D_{10})^2 \qquad (3.2\text{-}1)$$

where

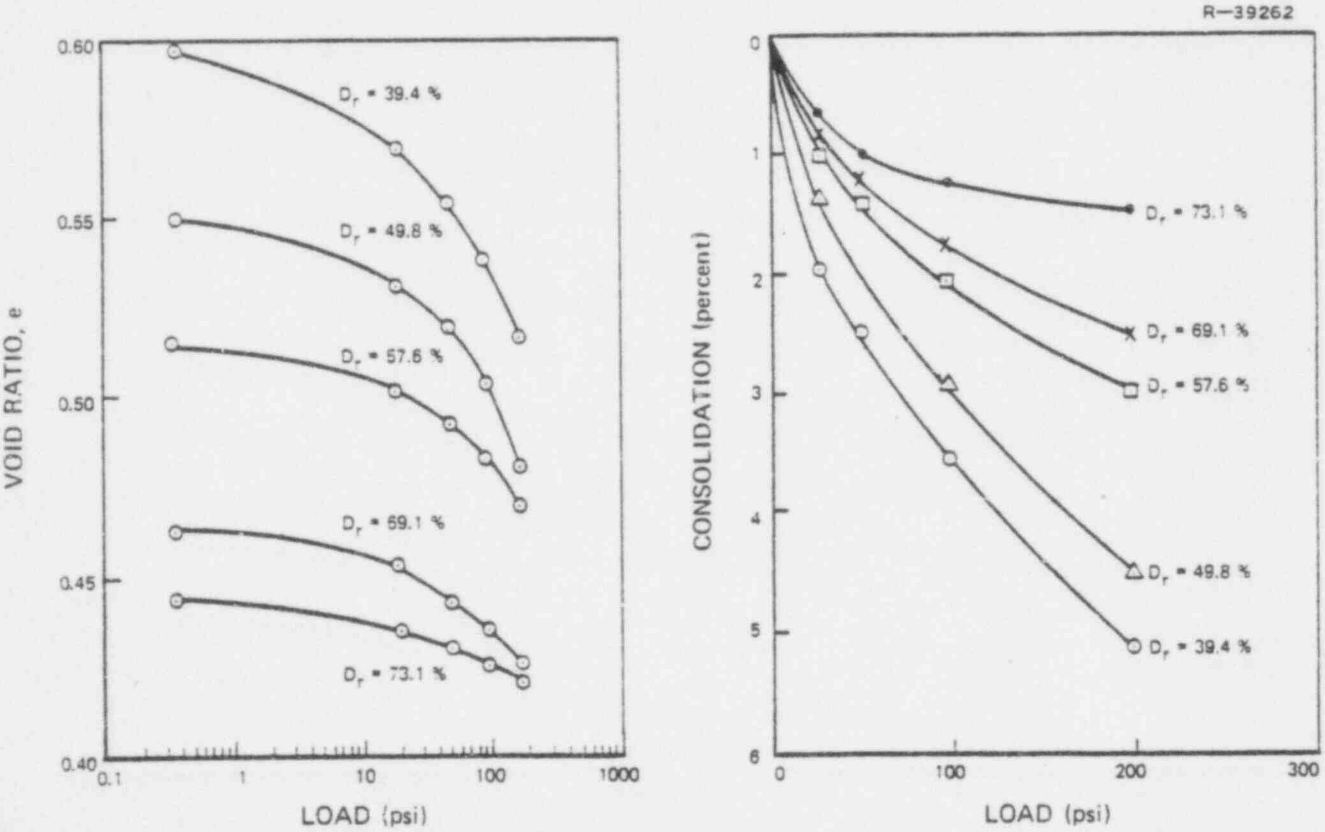
K = permeability in cm/sec

D_{10} = particle size in centimeters for which 10 percent of the total is finer than

This relationship was developed by Hazen (Ref. 14), based on laboratory data from clean sands, but yields reasonable estimates for most nonclay soils. Clays and clay-sand mixtures can be expected to have low permeabilities in the range of 10^{-5} to 10^{-9} cm/sec, depending on the type and percentage of clay.

1847 356

The compressibility for nonclay fills will be primarily a function of the compacted relative density. Figure 3.2-1 shows the compression under no lateral strain of a clean medium sand compacted to five different densities. The composition of the sand is shown in Figure 3.2-2. The compressibility at a relative density of 39.4 percent was over three times the compressibility at a relative density of 73.1 percent. Likewise, the compressibility of a clay fill is also a function of compacted density but is also highly dependent on the plasticity of the clay.

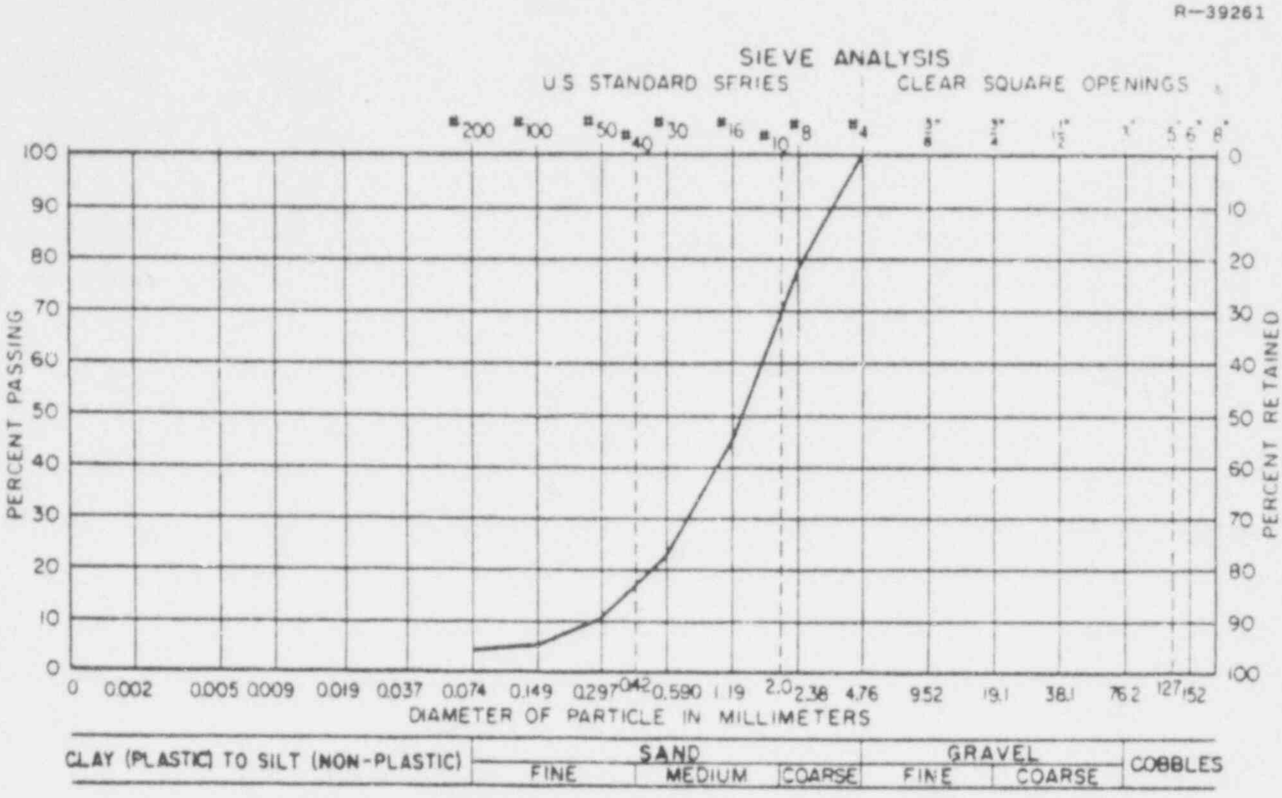


Note: D_r refers to the relative density

Source: Ref. 7

Figure 3.2-1 Compressibility of a Clean Medium Sand at Various Relative Densities

1847 357



Source: Ref 7

Figure 3.2-2 Composition of Sand Used in Compressibility Test

The general properties of a crushed salt, shale, basalt, and granite backfill are presented below:

3.2.2 Crushed Salt

- Placement Methods: Due to its low strength, salt can be readily crushed to less than 1/8 to 1/4 inch size, as is currently done underground in commercial salt mines. Hydrologic placement with saturated brine solutions is feasible. This procedure has been used in German potash mines where evaporite waste is transported back into the mine hydraulically using saturated brines (Ref. 15). Due to the salt's low strength, pneumatic stowing would probably be difficult because particulate breakup and severe dust problems. The salt could be placed and compacted

1847 358

mechanically. Compacted porosities on the order of 0.25 are probably achievable with careful placement techniques.

- Hydrologic Properties: Due to its solubility in fresh water, the permeability of crushed salt is not a simple parameter but depends on the salt content of the percolating water and may vary with time due to solutioning and/or precipitation of salt. Eilers (Ref. 16) compacted granulated salt finer than two millimeters in a Harvard-type miniature soil compaction device and compacted it to a porosity of 0.25 using a compaction effort equivalent to 100 percent of ASTM standard compaction. The intrinsic permeability, as measured in short duration tests with both oil and salt water, was found to be about 400 to 500 millidarcies. This equates to a water permeability of about 10^{-4} cm/sec. Had the tests been performed over an extended period with fresh water, the permeability would have undoubtedly increased rapidly as the salt dissolved.

  As suggested by DOE (Section 2.2.2), should the crushed salt in time creep and fuse into a solid mass, the backfill permeability would be similar to the natural salt formation -- i.e., very low.

- Mechanical Properties: In a research paper prepared for the Energy Research and Development Administration (ERDA), Hansen (Ref. 17) presents the results of compression tests on samples of crushed salt at various temperatures. The samples were composed of a uniform fine gravel ranging between about 1mm to 5mm in size. The samples were compressed without allowing lateral strain up to a stress of 4000 psi at temperatures of 21°C, 100°C and 200°C. The stress controlled loading was of two types: rapid loading at 10 to 50 psi/minute, and creep loading in larger increments allowing for 100 to 200 minutes of creep between increments. The volume change was found to be a function of stress level with little influence from

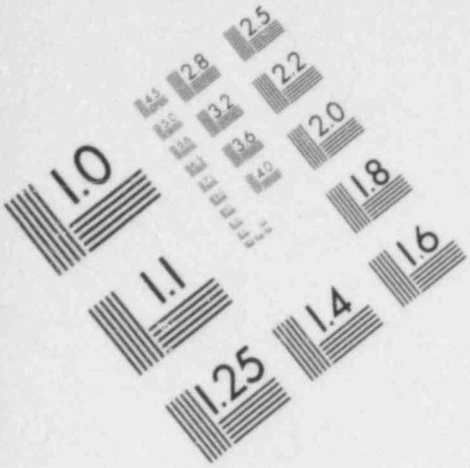
1847 359

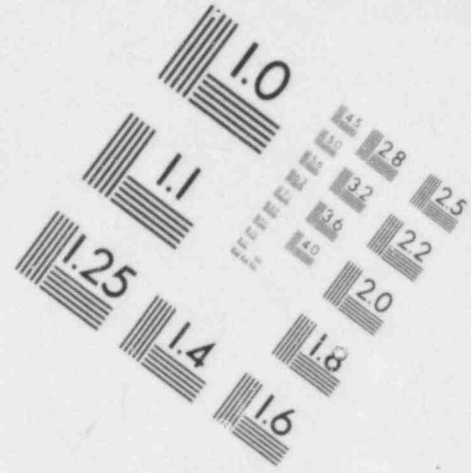
creep. Figure 3.2-3 is a summary plot of the test results, while Fig. 3.2-4 shows the results of one of the creep tests. It should be noted that the longest test was only about eight hours and consequently the effects of long-term creep was really not investigated. Le Comte (Ref. 18) presents a procedure for preparing artificial rock salt samples from pure halite powder. The grain size of the powder varied from 0.1 to 0.15 mm. The powder was pressed into truncated cones and compressed under 70,000 psi at 300°C for one day. The product was a rock salt sample with a porosity of about two percent and a density of 2.12 g/cm^3. The procedure supports the concept that crushed salt grains can be fused into solid rock salt under temperature, pressure and/or time. However, it is not possible to correlate the results of fusing fine salt grains at 70,000 psi to the more likely coarser gradation and much lower pressure (probably less than 1000 psi) anticipated in the depository.

- Chemical Behavior: A primary drawback of crushed salt backfill is its solubility. Circulating fresh water, given sufficient time, would dissolve all of the backfill. However, resaturation or circulation with saturated brines would not dissolve the salt and in fact could result in precipitation and filling of the voids. Nuclide retardation and adsorption in salt is believed to be nil (Ref. 19). Salt is known to be corrosive to many materials and is a poor medium for minimizing chemical attack.

- Advantages:

  - Available and inexpensive
  - Environmentally advantageous since it reduces the volume of salt requiring surface disposal
  - May recrystallize and/or fuze into solid rock salt under the influence of time, temperature, and pressure. The available data neither supports nor refutes this concept.





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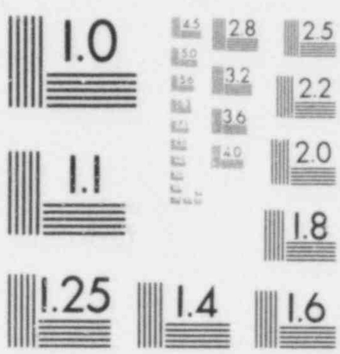
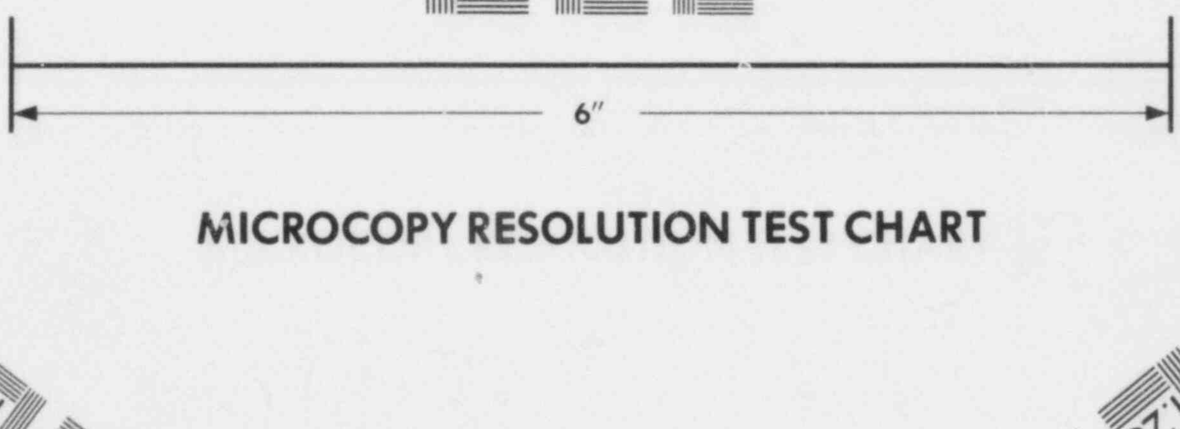
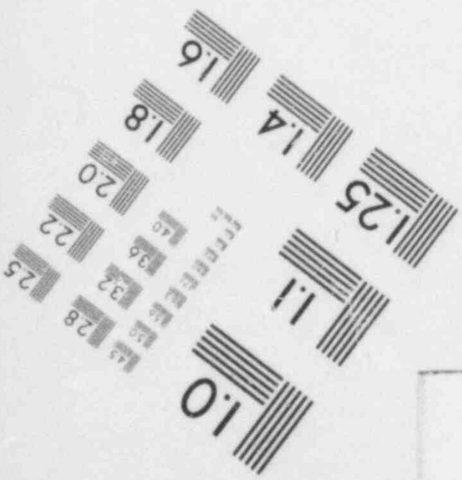
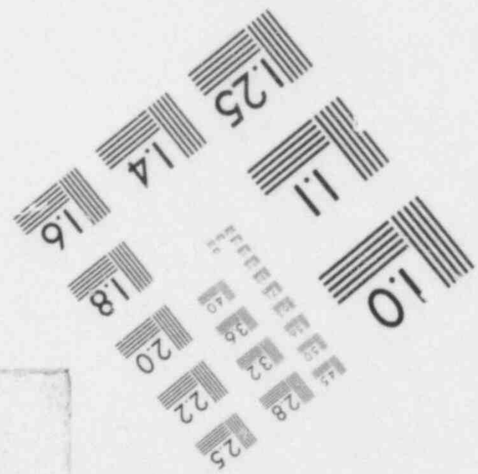
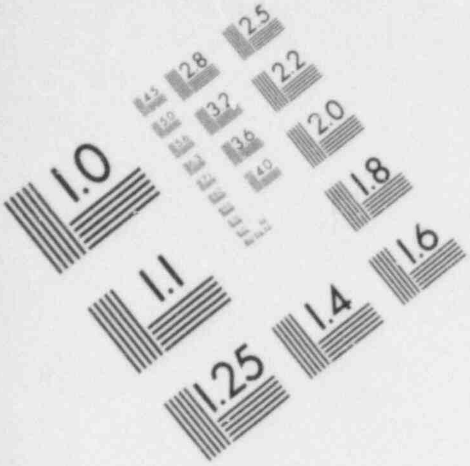




MICROCOPY RESOLUTION TEST CHART







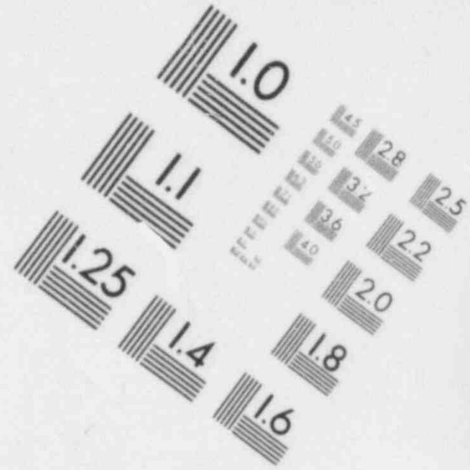


IMAGE EVALUATION
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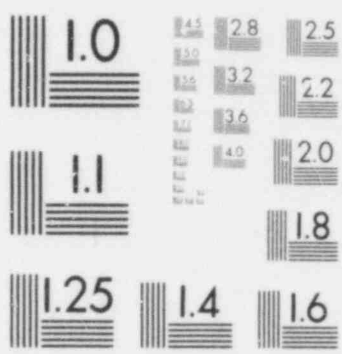

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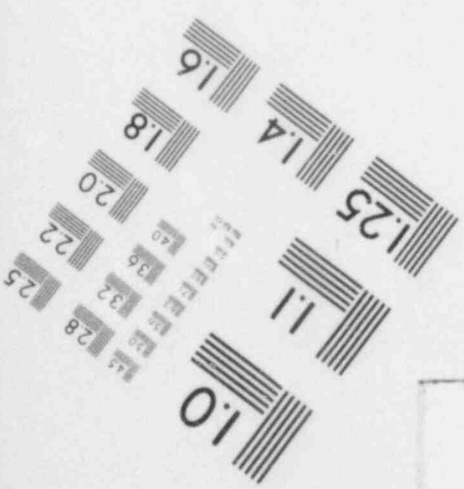
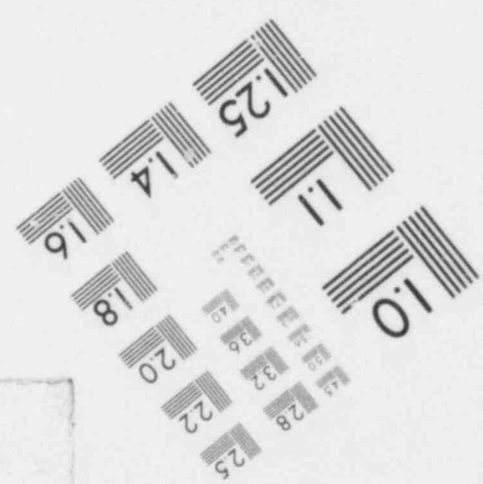
MICROCOPY RESOLUTION TEST CHART





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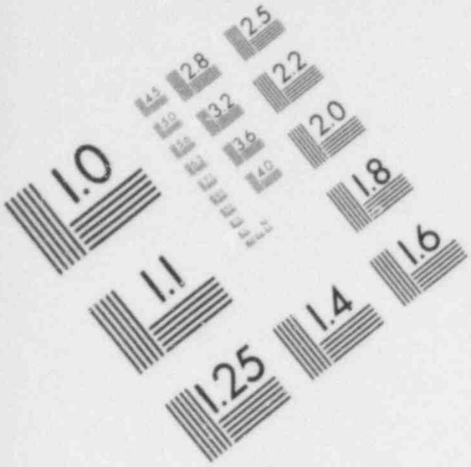

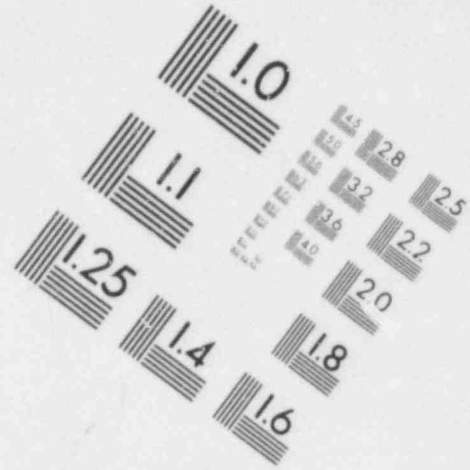

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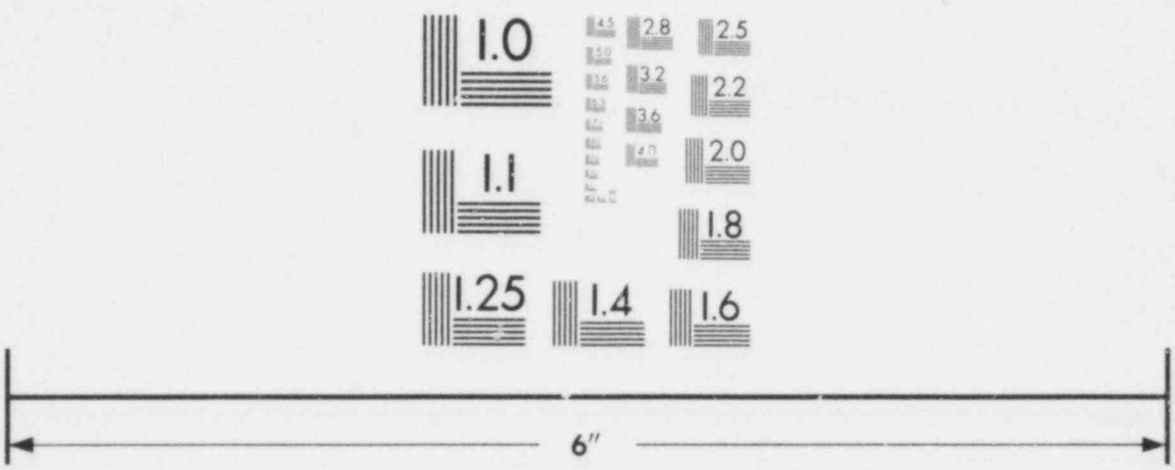

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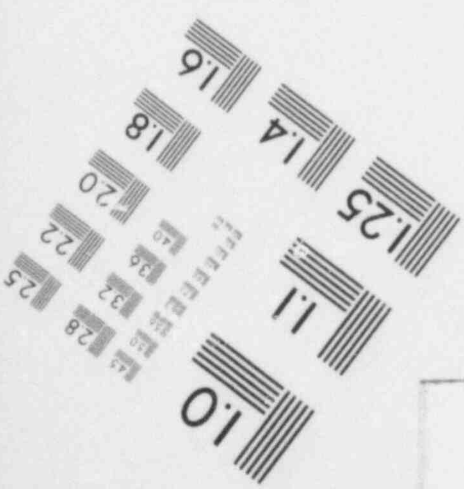
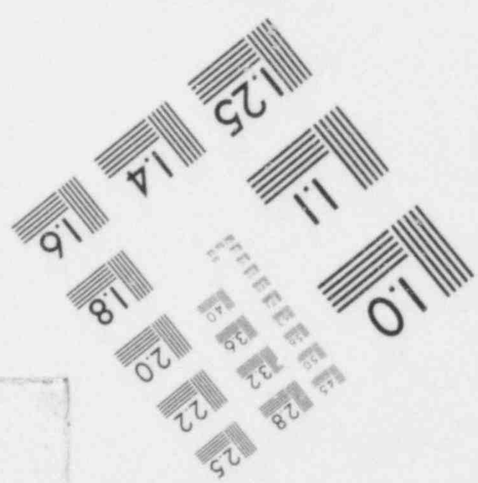




- Disadvantages:
  - Soluble in unsaturated water
  - Initial permeability is relatively high, on the order of 10^{-4} cm/sec
  - Compressibility is relatively high at high temperatures; experiencing a compression of about 20 percent strain at 2000 psi
  - No nuclide retardation
  - Corrosive medium.

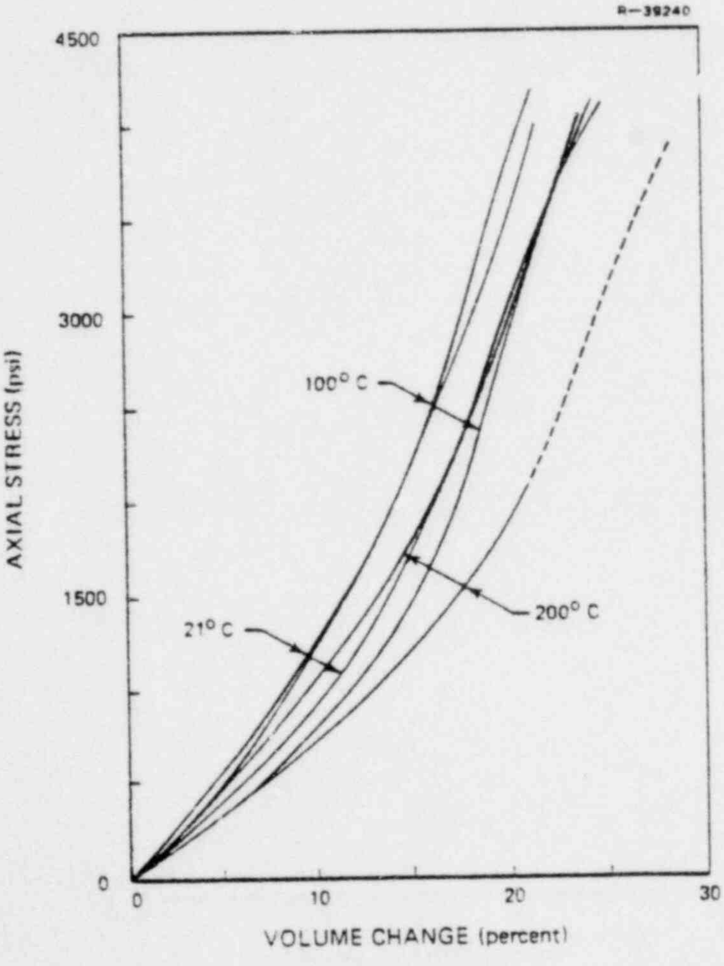
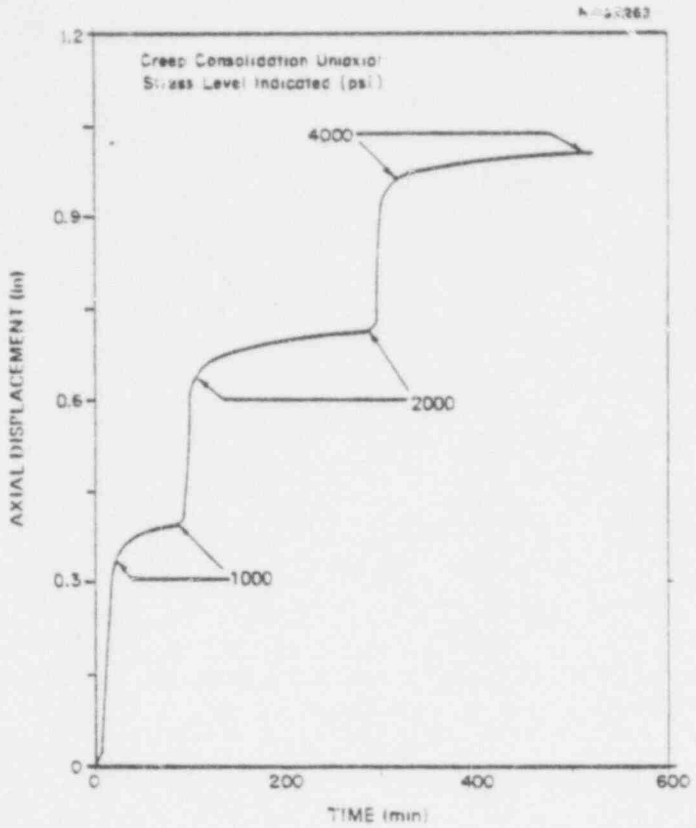


Figure 3.2-3 Compressibility of Crushed Salt at Various Temperatures

1843 001



Source: Ref. 17

Figure 3.2-4 Results on Creep Tests on Crushed Salt at 200°C

3.2.3 Crushed Shale

- Placement Methods: Excavated crushed shale can be placed by hydraulic, pneumatic and/or mechanic methods. After crushing, the softer, more plastic shales will tend to include a higher percentage of fines and decompose rapidly into clays upon contact with water. Hydraulic placement of these plastic shales would probably be undesirable since the result would be a very wet and compressible slurry type of fill. Pneumatic placement of the weaker shales may also be a problem due to particulate

1843 002

breakdown. Soderberg and Corson (Ref. 6) found that soft shales were difficult to place pneumatically. About three percent water was added to control dust, which made the shale too sticky to flow easily. It was also found that it was impossible to produce a uniform fill due to the breakdown of the shale particulates upon impact.

- Hydrologic Properties: The permeability of a compacted shale fill will depend a great deal on its decomposition during crushing and placement. Shales, such as bentonitic shales, which experience significant decomposition can be expected to exhibit permeability behavior similar to the clay fills discussed in Section 3.5. Such materials would have permeabilities on the order of 10^{-5} to 10^{-9} cm/sec. Shales which maintain their basic structure would behave similar to any well-graded silty crushed rock containing some clay and would have permeabilities on the order of 10^{-3} to 10^{-5} cm/sec. Porosities for both types of fills can be expected to be on the order of 15 to 30 percent.

- Mechanical Properties: As with permeability, the mechanical behavior of shale fill will be very dependent upon the amount of decomposition during weathering. A detailed discussed of the mechanical behavior of clay fills is presented in Section 3.5. In general, shale fills can be expected to be more compressible than nonshale rock fills.

- Chemical Behavior: Shale fills are insoluble, chemically stable, noncorrosive, and have high nuclide retardation factors. The high temperature produced by the waste canisters may adversely affect the shale by driving off the bounded water from the clay minerals. This problem is discussed in more detail in Section 3.5.

1843 003

- Advantages:

  - Available
  - Low permeability
  - Insoluble
  - Chemically stable and noncorrosive
  - High nuclide retardation

- Disadvantages:

  - Relatively high compressibility
  - May degrade and/or produce free water due to heating by canisters

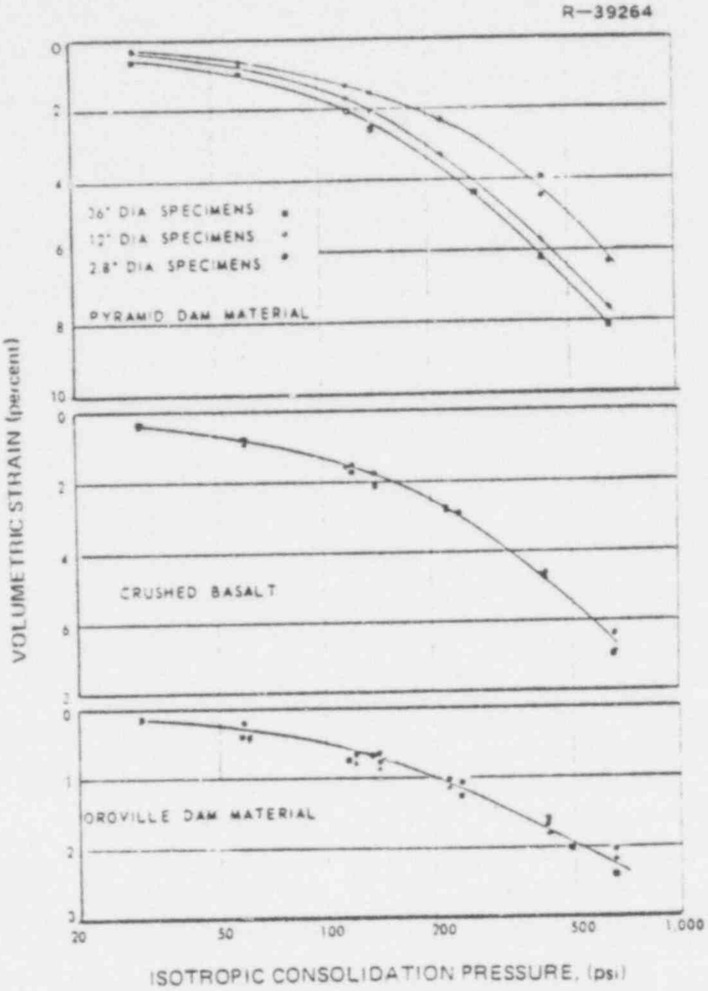
3.2.4 Crushed Basalt and Granite

- Placement Methods: Both basalt and granite are hard, durable rocks which will crush down into well graded silty sand and gravel-size particles. The maximum particle size and silt content will depend on the extent of the crushing and milling processes used. Due to their hardness, considerable effort would be required to break down the rock to less than about 1/2-inch. Both materials are ideally suited for hydraulic, pneumatic, and/or mechanical placement.

- Hydrologic Properties: The permeability would be essentially the same as any silty sand and gravel with similar gradation and density characteristics. Hazen's formula given in Eq. 3.2-1 can be used to estimate the permeability, which can be expected to range from about 10^{-1} to 10^{-3} cm/sec.

- Mechanical Properties: Figure 3.2-5 shows the compressibility of several samples of crushed basalt and rock fills. The figure indicates that the fills would be considerably less compressible than crushed salt or shale. However, they are still considerably more compressible than massive basalt or granite.

1848 004



Source: Ref. 7

Figure 3.2-5 Isotropic Consolidation of Molded Rock Fill Materials

- Chemical Behavior: The fills are insoluble, chemically stable, noncorrosive, and would not be adversely affected by the canister heat. Little is known about nuclide retardation in crushed basalts or granites, but it is undoubtedly less than shale and greater than salt.

- Advantages:

  - Available
  - Easy to place

1843 005

- Insoluble
- Chemically stable and noncorrosive
- Not adversely affected by heat
- Relatively low compressibility as compared to crushed salt and shale

- Disadvantages:
  - High permeability

3.3 CONCRETE/CEMENT

3.3.1 Introduction

Concrete, in many ways, is an ideal backfill with low permeability and compressibility. Clearly, though the cost of filling the entire depository with concrete would be high. Assuming a total depository volume of about 20 million cubic yards (cy) and a concrete cost of about $25/cy, the cost would be about $500,000,000. It may be more appropriate to use concrete backfill for plugs at critical locations such as the entrances into all waste storage rooms.

The general procedure for placing a concrete plug would probably include:

- Construct bulkheads, probably of reinforced concrete
- Pump in concrete under pressure
- Pressure grout contact zone between concrete and rock.

A more detailed discussion including data on plugs in deep South African mines is presented in Section 2.4.1 of Volume 1.

Concrete is an adaptable medium which can be engineered through its composition and use of additives to meet a wide range of physical and chemical characteristics. The behavior of concrete and the effects of cement additives have been extensively studied and documented in the civil engineering literature. Detailed information exists in Refs. 20 and 21. No attempt is made to duplicate this information in this report. Rather, a brief summary is presented of the essential properties of concrete as related to depository backfills. Information on seals and grouts is presented in Volume 1.

3.3.2 Hydrologic Properties

The permeability of concrete depends primarily on the type and gradation of the aggregate, amount of cement, amount of water, conditions during curing, and type of additives. The various types and mixtures of concrete exhibit permeabilities ranging from 10^{-6} to 10^{-10} cm/sec. The lower permeabilities are associated with concretes containing more cement, less water, and nonporous aggregates (Ref. 22). Mather (Ref. 23) tested various concrete samples with different cement types mixed with a fine-grain limestone aggregate and measured permeabilities ranging from about 10^{-9} to 10^{-10} cm/sec. The tests appear to be performed with samples which were only partially saturated. Since entrapped air can significantly reduce permeability, the permeability of similar saturated samples may have been as high as 10^{-7} to 10^{-8} cm/sec. Tests at Lyons, Kansas indicated a permeability of about 10^{-8} to 10^{-9} cm/sec (Ref. 24).

Concrete can be expected to have porosities ranging from about 0.10 to 0.20.

1843 007

3.3.3 Mechanical Properties

As with permeability, the mechanical behavior of concrete varies significantly depending on its composition and conditions during curing. In general, strength and rigidity increase with increasing cement content and curing time. Average values of unconfined strength range from about 2000 to 6000 psi and values of elastic modulus range from about 2×10^6 to 6×10^6 psi. Thus, concrete has deformation characteristics similar to most intact rocks.

During curing, concrete will shrink about 0.1 percent. However, expanding cements containing calcium sulfate and aluminate are available to reduce shrinkage and even develop a net swell during curing.

3.3.4 Chemical Behavior

Concrete is a chemically stable material but can be attacked by certain solutions such as acidic water, solutions of sodium or magnesium sulfate, and salt water. The literature contains a wealth of information relating to the use of additives to minimize or eliminate such reactions. Certain types of aggregates will react with the alkalies in cement and cause a rapid deterioration of the concrete. Reactive aggregates include charts, siliceous limestones and dolimites, rhyolites, dacites, andesites, siliceous shales, and phyllites. Use of such aggregates should be avoided. The long term performance of concrete in excess of hundreds of years represents an uncertainty.

The relatively mild temperature increase anticipated in the depository backfills -- probably less than 200°C -- is not expected to cause serious deterioration in the structural strength of the concrete (Refs. 25 and 26). Increase in permeability due to cracking is not documented.

No information on nuclide retardation in concrete was found.

3.3.5 Advantages/Disadvantages

Concrete has excellent properties for a depository backfill. It has low permeability, low compressibility and is insoluble. Also, with suitable additives, it can be made chemically stable in a wide variety of environments. The obvious disadvantage is its high cost, which may prohibit its use as the prime backfill material. However, it could be effectively utilized in plugs at critical depository locations.

3.4 SAND BACKFILL

For the purpose of this section, sand backfill is composed of grains of quartz, feldspar, or other inert, resistent minerals. The grains range in size from about 0.1 mm to 2.0 mm. Sand fill could be readily placed using hydraulic, pneumatic, and/or mechanical methods.

The permeability of a sand fill would depend on its gradation and density. The general comments on permeability, including Hazen's formula presented in Eq. 3.2-1 are applicable to sand fills. The approximate ranges in permeability for a sand fill are shown in Table 3.4-1.

Figure 3.4-1 shows permeability data on several different soil types and indicates the effect of void ratio on permeability. The void ratio is defined as the ratio of the void volume to the solid volume. The porosity of the sand fill is also a function of compacted density and grain size. It generally ranges from about 0.25 to 0.04.

1843 009

TABLE 3.4-1

SAND FILL PERMEABILITIES

Type*	Permeability Range (cm/sec)**
Sandy Silt	$5x10^{-4}$ to $2x10^{-3}$
Silty Sand	$2x10^{-3}$ to $5x10^{-3}$
Very Fine Sand	$5x10^{-3}$ to $2x10^{-2}$
Fine Sand	$2x10^{-2}$ to $5x10^{-2}$
Fine to Medium Sand	$5x10^{-2}$ to 10^{-1}
Medium Sand	10^{-1} to $1.5x10^{-1}$
Medium to Coarse Sand	$1.5x10^{-1}$ to $2x10^{-1}$
Coarse Sand and Gravel	$2x10^{-1}$ to $5x10^{-1}$

*Based on Unified Soil Classification System.

**From Ref. 27.

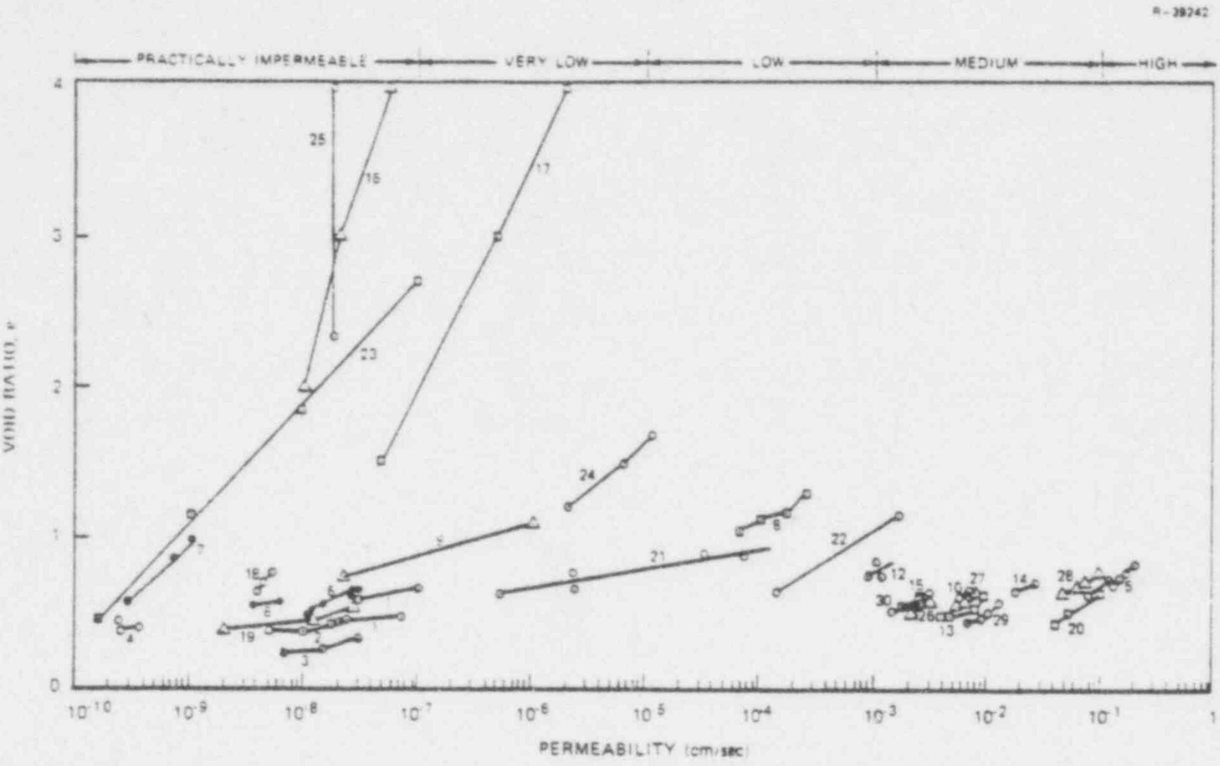
The compressibility of the fill would depend on grain size, mineralogy, and compacted density. Figure 3.4-2 shows the results of high-stress compression tests on several representative sands. In general, the compressibility of sand fill is similar to crushed salt and less than clay. At high stresses sand particles can break down and the incremental compressibility for sands can exceed clays.

The sand fill would be insoluble, chemically stable, noncorrosive, and would not be adversely affected by canister heat. Although less than clays and shales, sands do exhibit significant nuclide retardation behavior.

The <u>advantages</u> of sand fill include:

- Availability
- Ease of placement
- Chemical and thermal stability

1843 010



Source: Ref. 14

SOIL IDENTIFICATION CODE

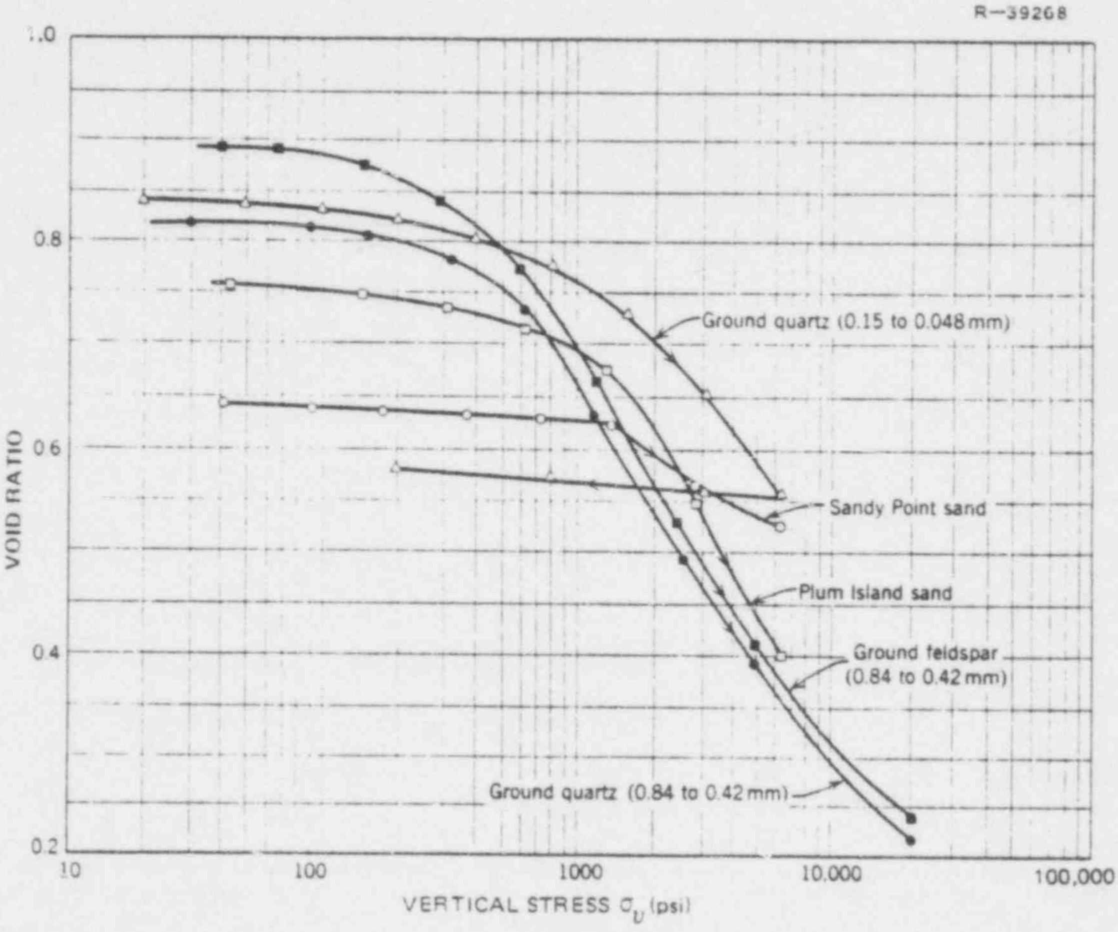
1 Compacted caliche
2 Compacted caliche
3 Silty sand
4 Sandy clay
5 Beach sand
6 Compacted Boston blue clay
7 Vicksburg buckshot clay
8 Sandy clay
9 Silt-Boston
10 Ottawa sand
11 Sand—Gaspee Point
12 Sand—Franklin Falls
13 Sand-Scituate
14 Sand—Plum Island
15 Sand—Fort Peck
16 Silt—Boston
17 Silt—Boston
18 Loess
19 Lean clay
20 Sand—Union Falls
21 Silt—North Carolina
22 Sand from dike
23 Sodium—Boston blue clay
24 Calcium kaolinite
25 Sodium montmorillonite
26—30 Sand (dam filter)

Figure 3.4-1 Permeability of Various Soils

1843 011

- Significant nuclide retardation
- Relatively low compressibility compared with clay.

The <u>disadvantages</u> include high permeability.



Source: Ref. 14

Figure 3.4-2 Results of High-Stress, Confined Compression Tests on Several Sands

1843 012

3.5 CLAY BACKFILL

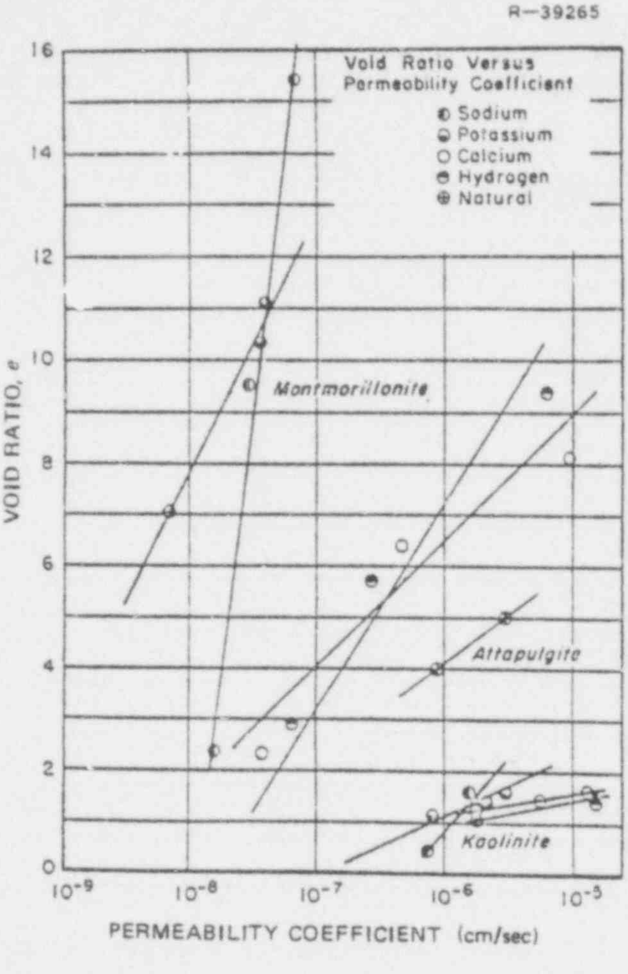
Clay fill will probably be mechanically placed. Although clay can be slurried and placed hydraulically, this would not be appropriate for a depository, since it would result in a very wet, weak slurry which would drain very slowly. As with shales (see Section 3.2.3), pneumatic stowing may be difficult.

The permeability of a compacted clay depends on:

- Type and percent of clay mineral present
- Compacted density or void ratio
- Compaction procedure, including type of compaction and moisture content.

Figure 3.5-1 indicates the variability of permeability with void ratio for various types of clay. Figure 3.5-2 shows the effect of compaction procedures, indicating that permeability decreases for higher compacted densities and high compacted water content. In general, the permeability range of compacted clays range from about 10^{-5} to 10^{-9} cm/sec. The porosity will range from about 0.3 to 0.6.

The compressibility of clay backfill is very much dependent on the clay type and initial void ratio. High void ratio, highly plastic clay slurries can compress to less than 20 percent of their initial volume. Conversely, well-compacted clay fill may compress only slightly more than a sand fill. As with permeability, the compressibility of the clays depend on both clay type and compaction procedures. Figure 3.5-3a shows the compression of several remolded clay slurries and Fig. 3.5-3b indicates general ranges for types of clays based on Fig. 3.5-3a. Figure 3.5-4 shows the compression of a compacted clay for both kneading compaction and static compaction.



Source: Ref. 28

Figure 3.5-1 Permeability of Various Remolded Clay Samples

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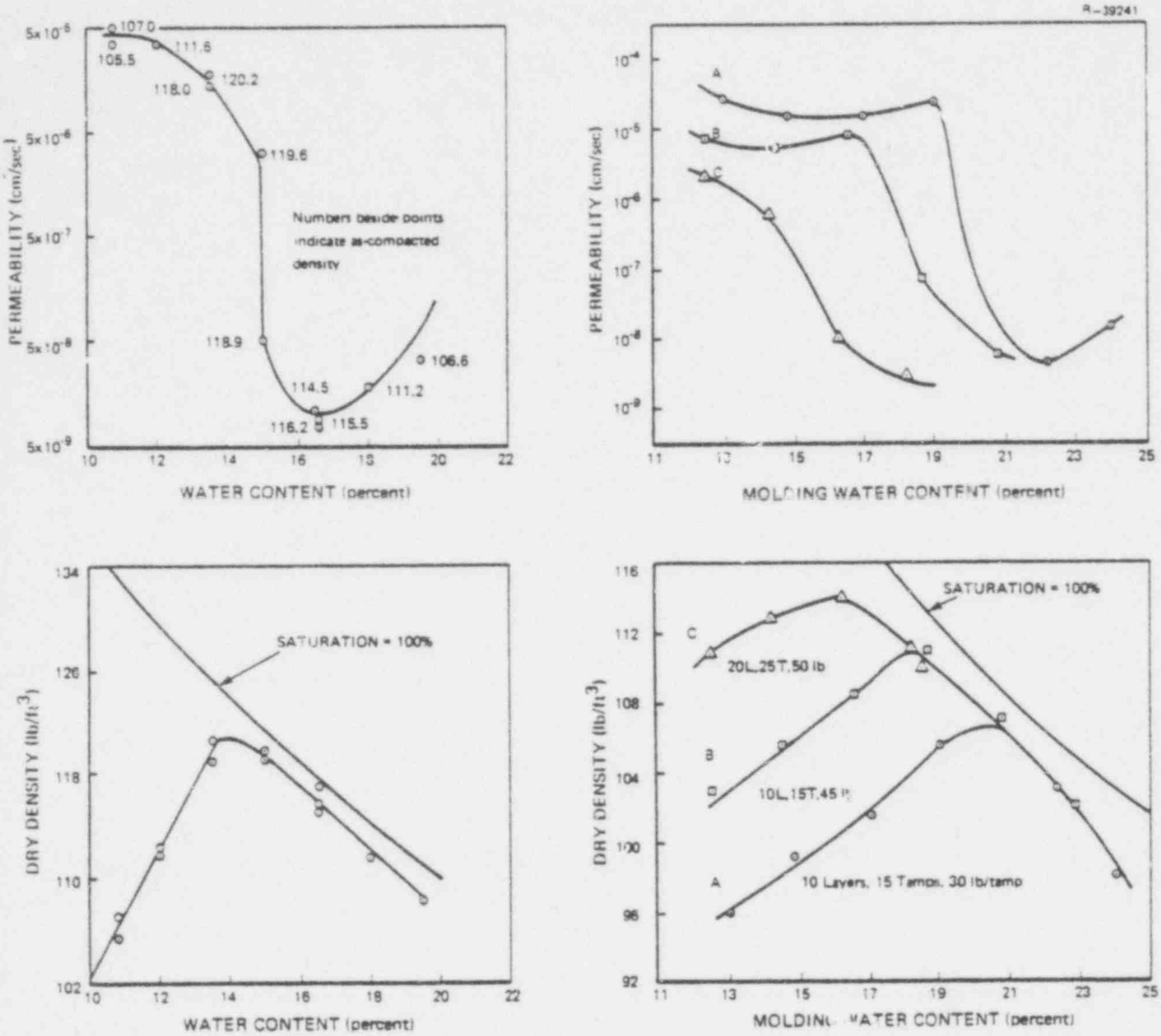

Source: Ref. 29

Note: The molding water content is defined as the ratio of the water weight to the soil weight

(a) Permeability vs water content for AASHO ROAD test soil-kneading compaction

(b) Permeability vs molding water content for samples of SILTY CLAY prepared at 3 compactive efforts

Figure 3.5-2 Permeability at 100% Saturation for Samples of Silty Clay Prepared at 3 Compactive Efforts

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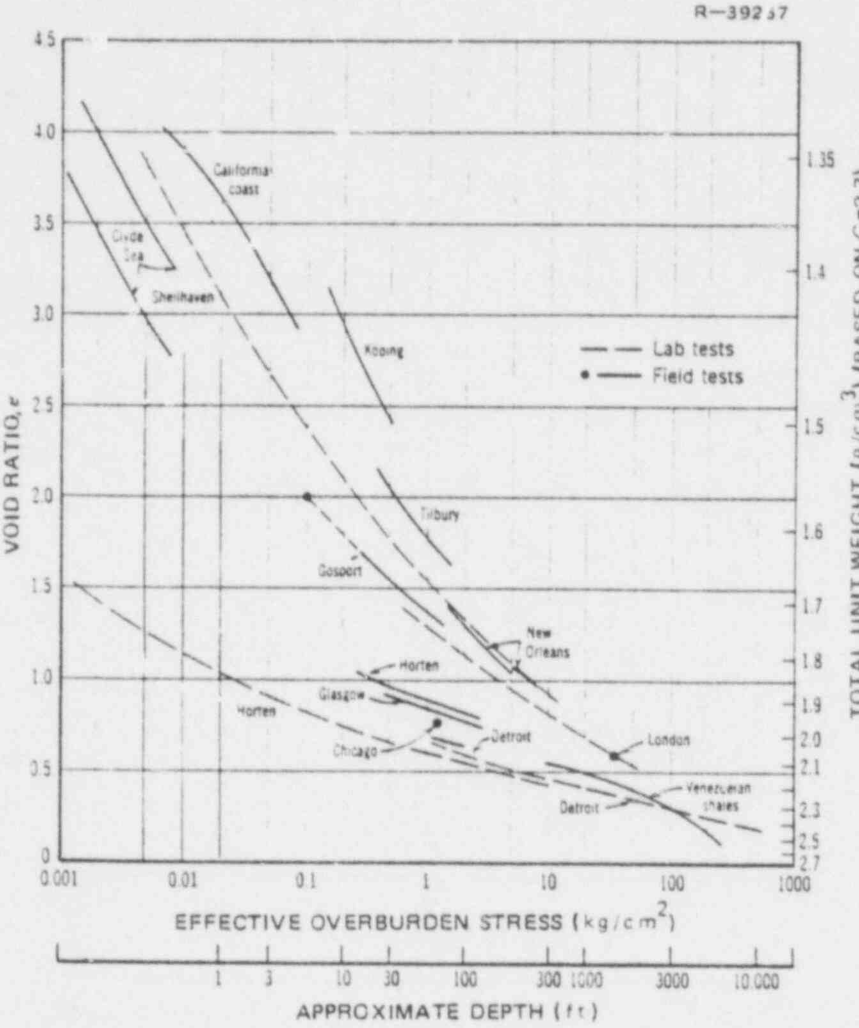

Source: Ref. 14

Figure 3.5-3a Compressibility of Various Clays

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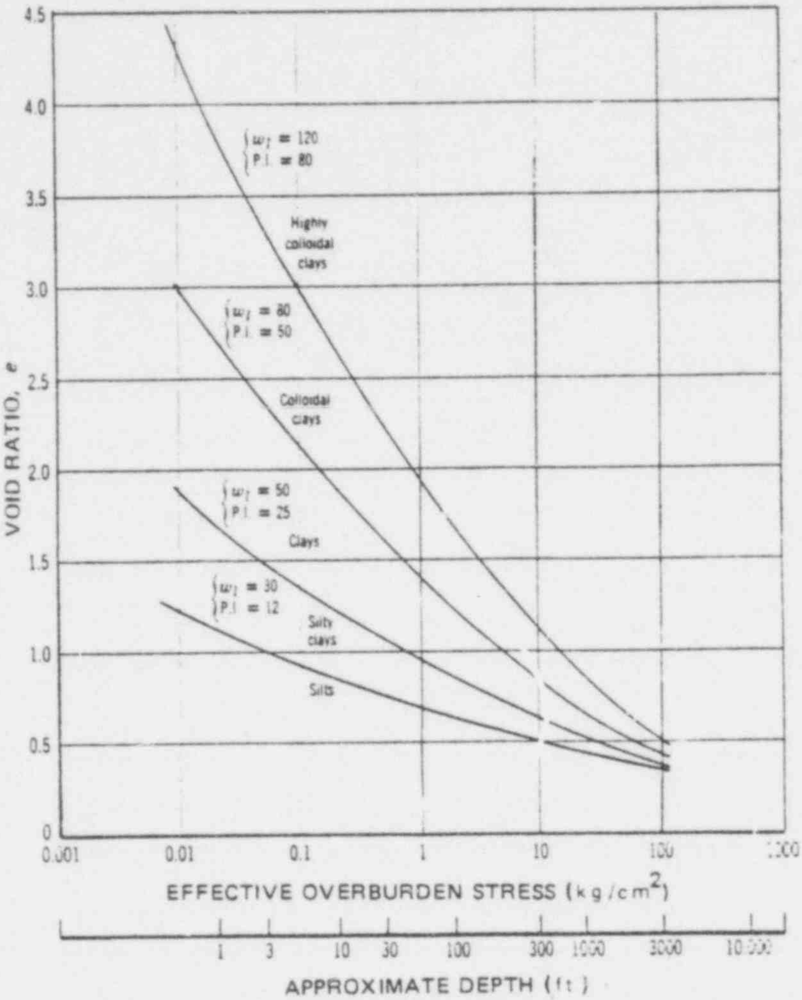

Note: The symbols ω_ℓ and P. I. refer to the liquid limit and plastic index respectively. They are used in the classification of clay types.

Source: Ref. 14

Figure 3.5-3b General Ranges in Compressibility of Clay Types

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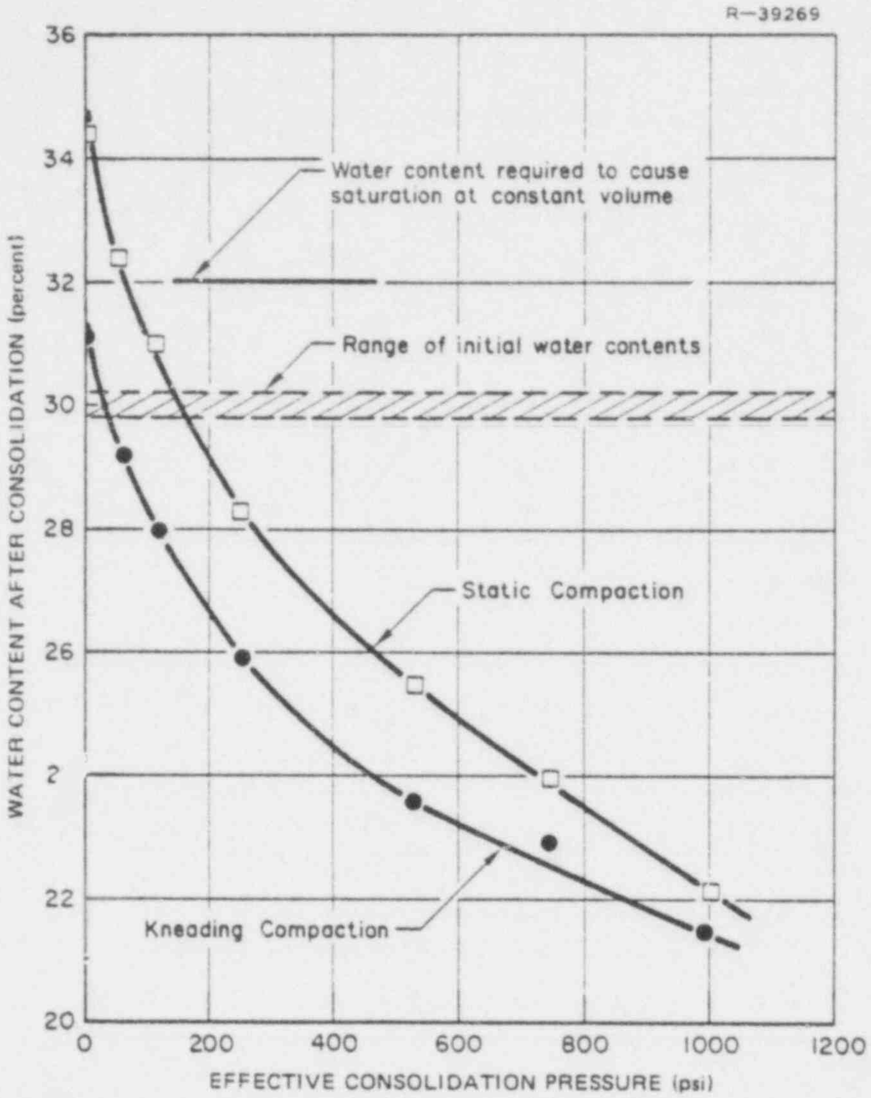

Source: Ref. 30

Figure 3.5-4 Compressibility of a Compacted Clay for Two Different Compaction Methods

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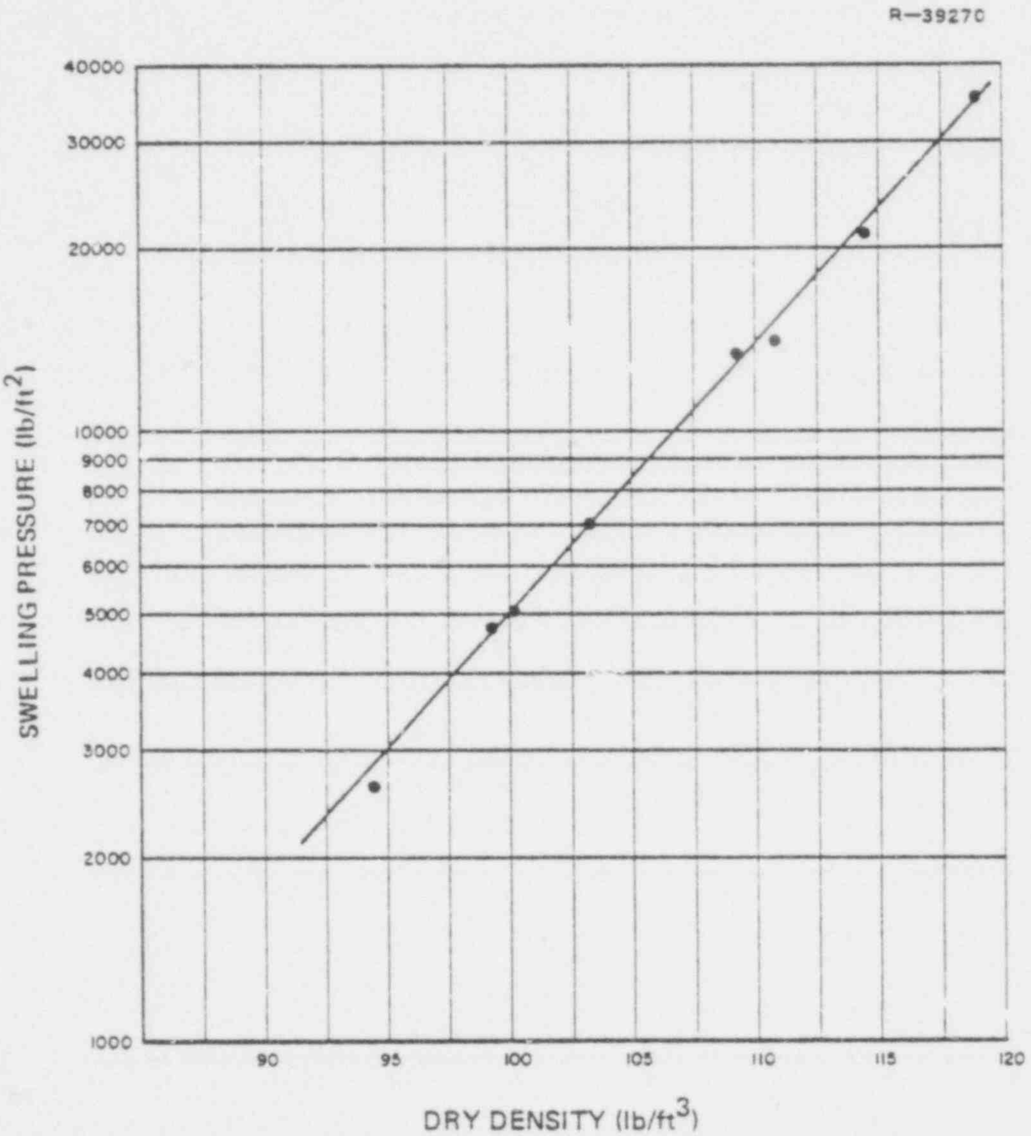
Compacted clays will tend to swell when saturated. The swell pressure increases with increasing compacted density, as shown on Fig. 3.5-5. Generally clays containing

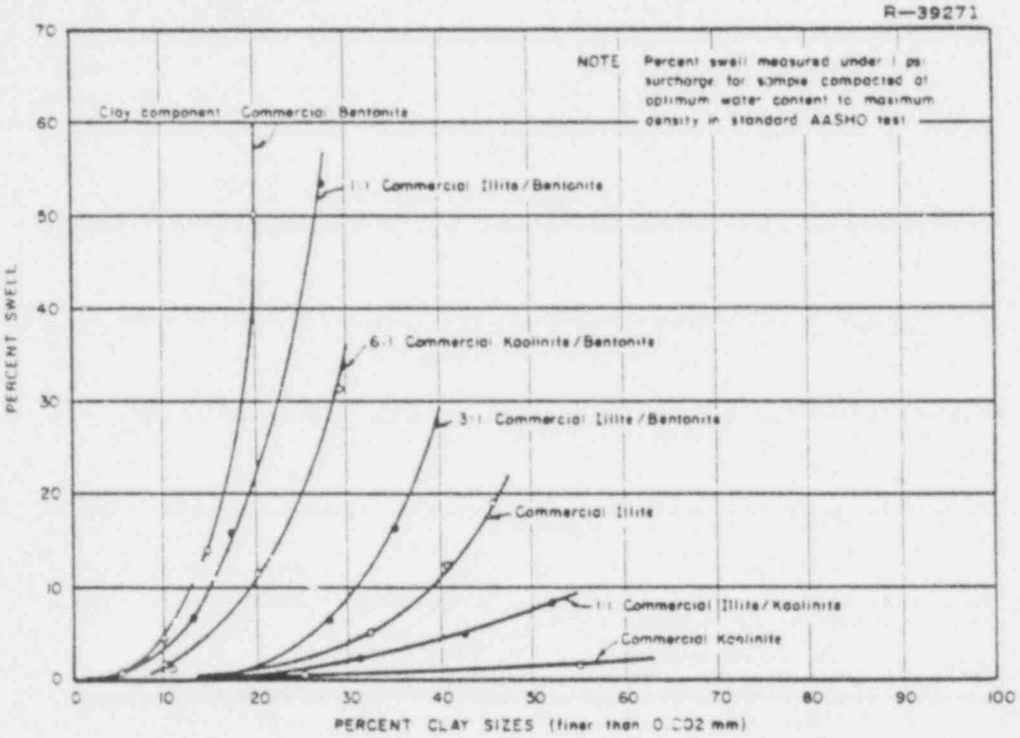


Source: Ref. 31

Figure 3.5-5 Effect of Varying Density on Swelling Pressure for Constant Moisture Content Samples

1843 019

bentonite or montmorillonite exhibit high swell pressures, those containing illite exhibit less, and those containing kaolinite exhibit very little. The effects of clay type are shown in Fig. 3.5-6. The data shown in the figure is for clay containing 10 percent montmorillonite with a plastic index of 25 percent. At high densities the clay developed pressures in excess of 100 psi. Although the swelling pressures would be too small to have much effect on the stability of the depository openings, it would produce a tight contact between the fill and the roof.



Source: Ref. 31

Figure 3.5-6 Relationship Between Percentage of Swell and Percentage of Clay Sizes for Different Types of Soil

1843 020

1843 019

The clay fill would be insoluble, chemically stable, noncorrosive, exhibit a very high nuclide retardation behavior, and swell on contact with water (if compacted and not saturated). The anticipated 200 to 300°F fill temperature produced by the canister heat is not enough to drive off any of the bounded clay water. Thus, the clay can be considered thermally stable unless it is heated to much higher temperatures.

The advantages of clay fill include:

- Low permeability
- Swells on contact with water (if compacted and not saturated)
- High nuclide retardation behavior.

The disadvantages include:

- Relatively high compressibility
- Not easily placed
- Not always readily available and expensive to prepare.

3.6 SUMMARY

A data base is provided for backfill material properties. An evaluation of these properties indicates the following:

- Crushed salt exhibits on initially high permeability, on the order of 10^{-4} cm/sec. The concept that the salt will eventually fuse into solid rock salt is neither supported nor refuted in the available literature.

1843 021

- Shale provides a low permeability backfill with high nuclide retardation. However, it is highly compressible and may produce free water due to heating by waste canisters.

- Crushed hard rock has a very high permeability, 10^{-3} to 10^{-1} cm/sec, which is a significant disadvantage.

- Concrete would be a very good material for depository backfilling were it not for its high cost. It may be effectively used in plugs at critical depository locations.

- Sand has a very high permeability, 10^{-3} to 10^{-1} cm/sec. However, sand may be combined with clay to produce a backfill with excellent properties. The primary disadvantage would be its low strength and rigidity, and cost.

- A clay backfill is expensive, difficult to place, and has a high compressibility. However, its low permeability and high retardation behavior might make it an attractive backfill material.

4. INSTRUMENTATION AND MONITORING

The repository should not <u>require</u> monitoring to assure the protection of the health and safety of the public because of the hundreds or thousands of years of monitoring that may be required and the probable extreme problems associated with remedial action. However, it may be desirable to monitor the repository performance as long as possible to provide an additional margin of safety. Although such monitoring will probably be too short-lived to be meaningful for properly performing repositories, the monitoring could identify major short-term malfunctions in the waste containment system. It may also provide an opportunity to gather relevant data for future repository evaluations.

The details of the instrumentation and monitoring will depend on the site environment and predicted repository performance. In general, the following elements might be included at the repository site.

- <u>Underground Monitoring</u>

  <u>Temperature</u>: Sufficient data to determine the general temperature profile around the depository.

  <u>Deformation</u>: Sufficient data to determine the general deformation characteristics around the depository openings and in the overlying rock formations.

  <u>Water pressure and quality</u>: Sufficient piezometer data to monitor the general depository, particularly critical in any overlying aquifers.

1843 023

Radiation: Sufficient data to detect and track any radiation release.

Waste canister performance: For selected canisters, the critical parameters such as temperature, corrosion and radiation should be monitored. Canister movement should also be monitored.

- Above Ground Monitoring: This may include: surface water quality, air quality, surface deformations (subsidence and/or heave), near-surface temperatures, and radiation levels in soils.

Away from the actual repository site the following may be monitored:

- Surface water quality
- Groundwater levels and quality (especially in aquifers)
- Well water quality
- Radiation levels in soils.

Appendices B and C of Volume 1 present a brief summary of borehole geophysical methods and borehole instrumentation techniques. This information will not be repeated in this volume.

1843 024

5. DISCUSSION OF POTENTIAL BACKFILL REQUIREMENTS

5.1 INTRODUCTION

The purpose of this chapter is to discuss the potential backfill requirements as related to structural, hydrologic, chemical, and economic considerations. Specific requirements are not defined. General comments in terms of the site environment, repository design, and projected waste form performance are presented.

5.2 STRUCTURAL CONSIDERATIONS

The structural purpose of the backfill is to minimize post-decommissioning deformation which might result in increased permeability. The increased permeability could be in the immediate vicinity of the depository, such as increased fracturing around the openings, and/or induced fracturing in the overlying formations. Fractures around the openings provide a potential pathway to flow along the storage rooms and tunnels which could connect through shafts and/or geologic flaws to the biosphere. Depending on the behavior of the rock, fractures in the overlying formations could lead to an increase in the permeability of the depository and/or barrier beds. This could result in inflow of water, possible dissolution of the depository layer in the case of salt, and potential pathways to the biosphere. In general, thinly interbedded formations are more susceptible to fracturing because of the low shear strength between beds.

For simplicity, it is appropriate to consider several idealized pillar and fill backfill performance scenarios. These include:

- Stable Pillars and Narrow Roof Spans: The depository is designed such that the pillars do not fail and the effects of roof fracture zones are very local. Under these conditions, the only deformation problem is the increased fracturing around the openings. For most cases, the extent of the fracturing about the opening cannot exceed the width of the rooms. The three backfill cases, as illustrated in Fig. 5.2-1 include:

  Rigid Fill: This will effectively eliminate additional roof spalling and increased fracturing.

  Compressible Fill: This will minimize the additional roof spalling and fracturing that could occur.

  No Fill: Maximum fracturing.

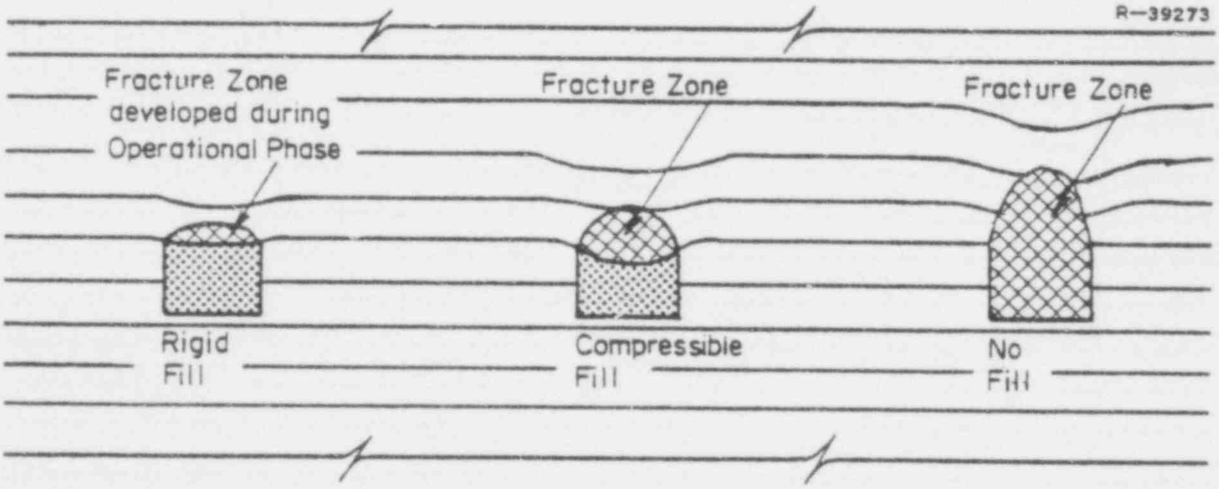


Figure 5.2-1 Illustration of Induced Fracture Zones Around Room Openings with Stable Pillars

1843 026

- Stable Pillars and Wide Roof Spans: This is similar to the case above, but with wide room spans which could result in the development of a more extensive roof fracture zone including possible overlapping of fracture zones between openings. Under these conditions, it might be possible for the zone of fracturing to migrate upward into overlying layers.
- Unstable Pillars: Due to creep, progressive failure, and/or other modes, the pillars eventually are overstressed and fail. This could lead to large scale deformation and cracking in the overlying formation. This situation is illustrated in Fig. 5.2-2. The three backfill cases include:

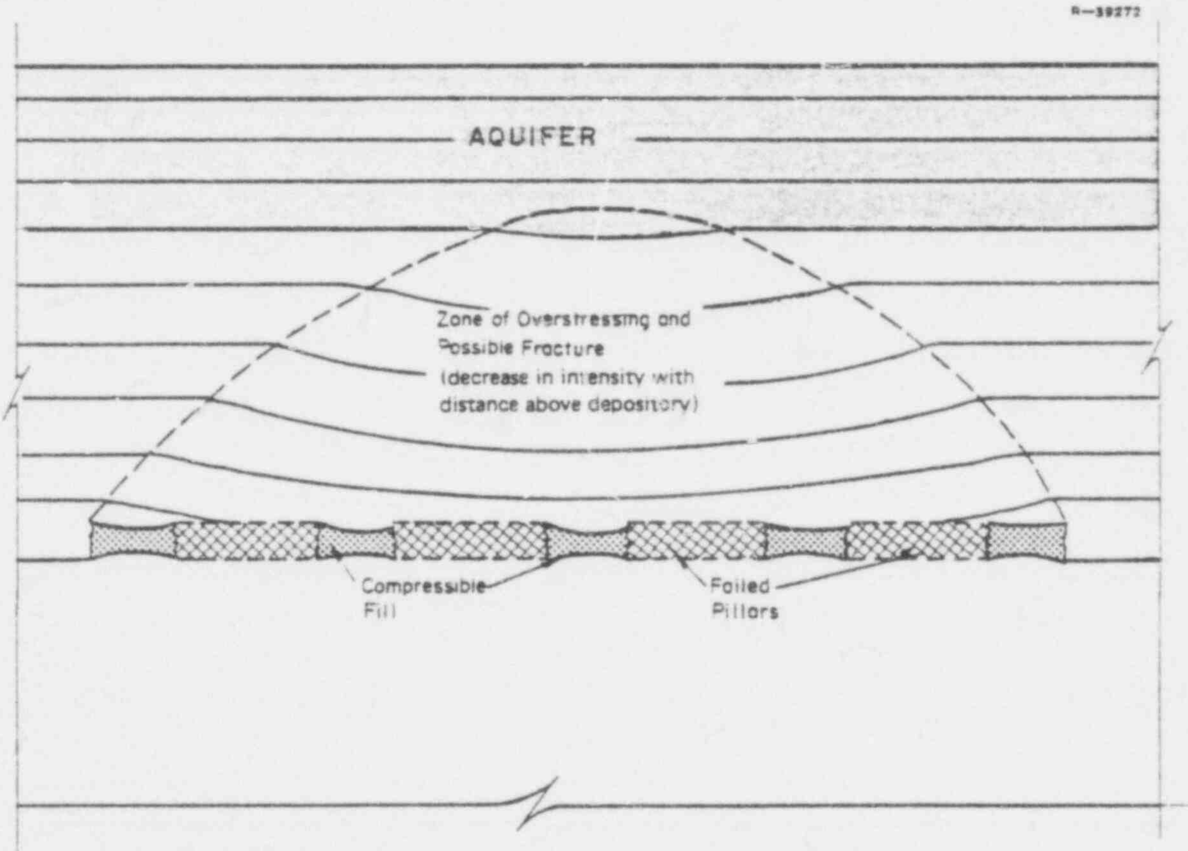


Figure 5.2-2 Major Deformation Associated with Pillar Failures

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Rigid Fill: The backfill accepts a significant portion of the load and the pillars do not fail. Additional major deformation does not occur.

Compressible Fill: Depending on the relative stiffness of the fill and the depository rock, the fill may minimize the fracturing to an acceptably small zone above the depository. However, in general, the fill would be too compressible to eliminate pillar failure. This is illustrated on Fig. 5.2-3.

No Fill: Maximum deformation, which could extend to the surface and result in subsidence exceeding 60 percent of the room height for wide spans (Ref. 32).

The accurate modeling of the processes described above is a very complex problem which has apparently never been performed. However, to predict the long-term deformation behavior around the depository for various backfill properties, it may be necessary to develop such a model. The following are suggestions for an initial modeling effort.

- Appropriate deformation characteristics of the backfill under a variety of temperature conditions and confinement must be established.

- Appropriate deformation characteristics of the host rock types both before and after fracturing must be known.

- Determine the temperatures in the backfill and the rock media as a function of time. Post-decommissioning thermal analysis of a repository in bedded salt is given in Appendix A.

- Model, initially two-dimensionally, the interaction of pillars under a variety of conditions (see Volume 4, Section 6).

The method most likely to be successful would be a finite element method of solution.

- Examine, as an upper bound, the resulting stresses above the depository excavations if all pillars fail. Then, using appropriate failure criteria for the overlying rock strata, compute the maximum level to which fractures, and thus increased fracture permeability, would occur. Increased permeability may also occur in existing natural fractures of planes of weakness.

Most backfills will be very compressible compared to the intact depository rock and pillar, as illustrated in Fig. 5.2-3. The only exception appears to be concrete. Figure 5.2-4 presents the probable ranges in deformation behavior for various types of backfill and intact depository rock. Assuming complete pillar collapse with the compressibility of the failed pillars identical to the backfill, 25-foot high rooms and a 2000-foot deep depository, the resulting deformation at the depository elevation would be:

No Backfill	25 feet
Clay Fill	5 to 9 feet
Sand Fill	3 to 5 feet
Crushed Salt Fill	6 feet
Crushed Basalt, Granite Fill	2 to 4 feet

Although complete pillar collapse will not occur, the above deformation values are an upper bound estimate of the magnitude of the potential vertical deformation.

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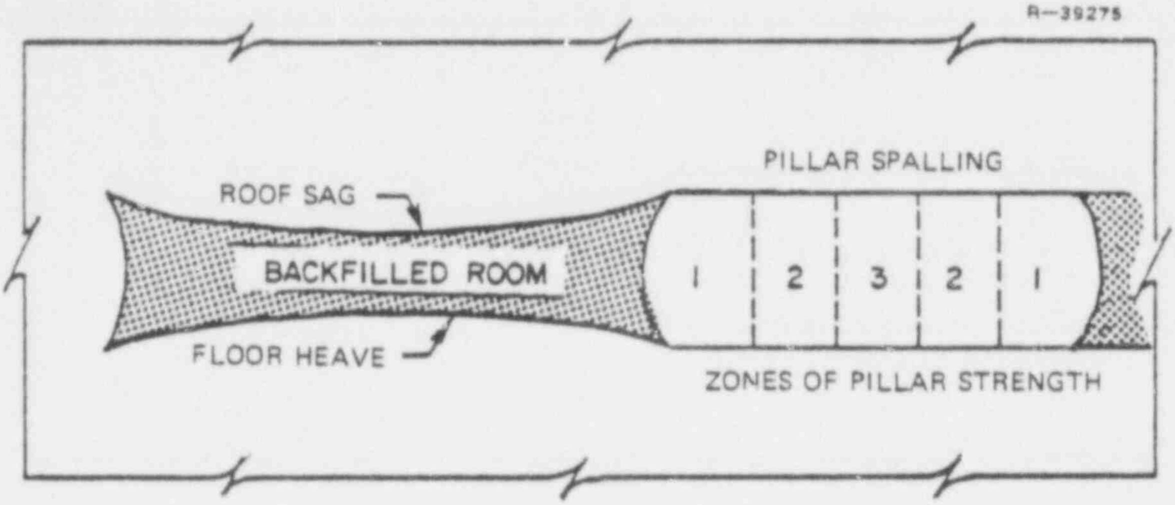

Note: Fill may increase strength and confinement of Zone 1

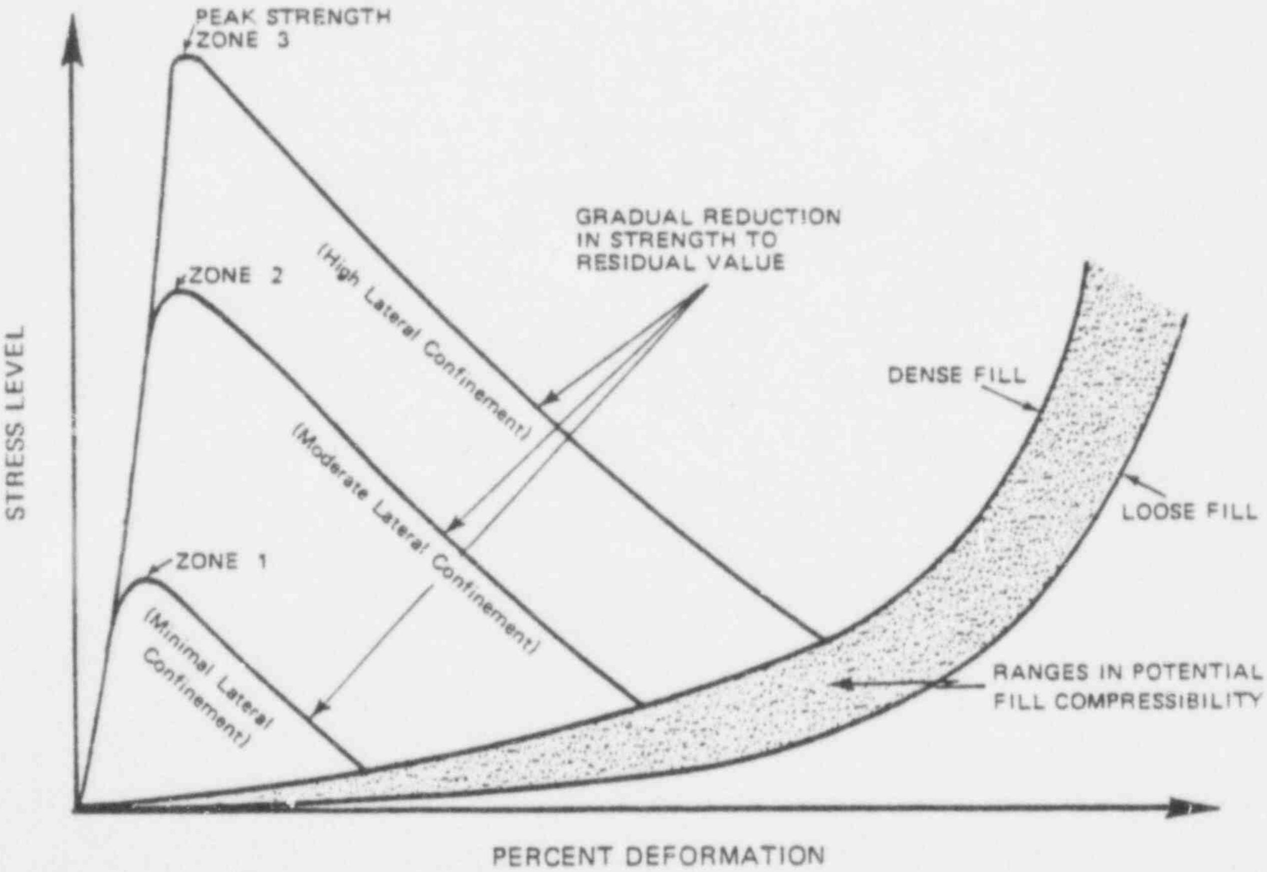

Figure 5.2-3 Illustration of Backfill and Pillar Deformation Behavior

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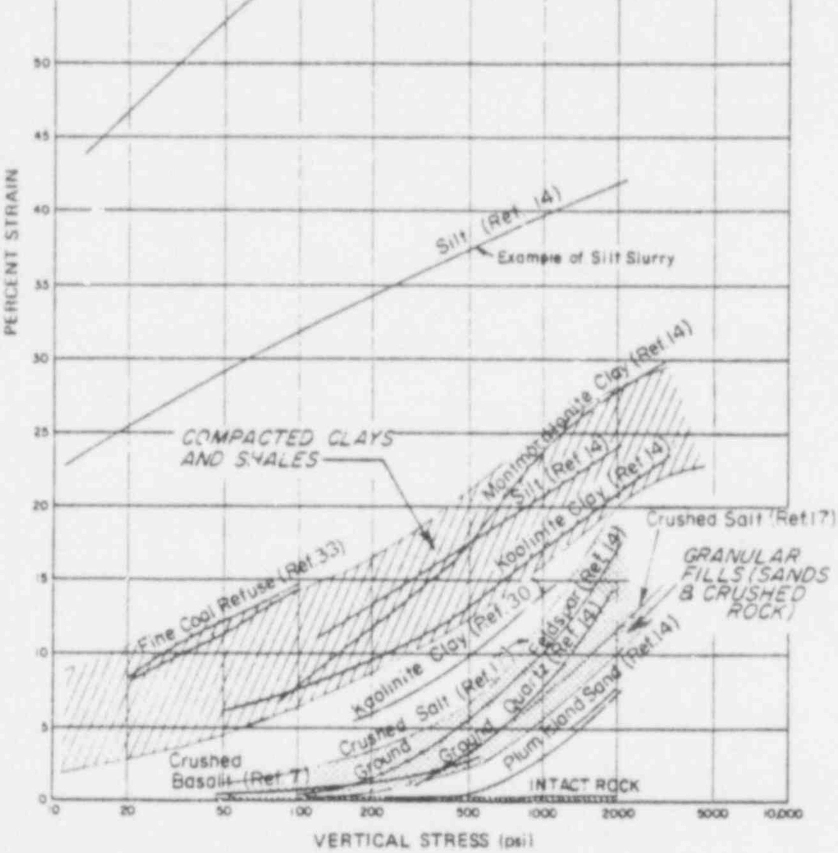

NOTE: Based on no lateral strain consolidation data; where required a poisson's ratio was assumed to convert isotropic consolidation data.

Figure 5.2-4 Deformation Behavior for Various Materials

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Subject to rigorous analysis, the above concepts lead to the following general conclusions concerning structural requirements:

- It is unrealistic to use backfill to stabilize the pillars. Any economically practical backfill will not be stiff enough to significantly reduce pillar stress. Thus, the pillars must be designed to be stable for the critical life of the depository.

- Presently, it is prudent to use relatively narrow rooms on the order of 15 to 25 feet to eliminate significant fracturing caused by roof spalling. However, detailed modeling of a specific site and depository design may indicate that wide rooms in conjunction with a granular backfill will result in acceptable roof fracturing.

- For adequately designed pillars and narrow openings, the difference between using a well-compacted, dense fill, such as crushed rock, and using a soft-compressible fill, such as clay, may be minor. In fact, the advantages of complete filling over partial filling may be relatively minor.

On the other hand, it may be desirable to use a stiff backfill such as concrete at critical locations within the depository to plug any continuous groundwater pathways along the roof fracture zones between the storage rooms and the shafts.

5.3 HYDROLOGIC CONSIDERATIONS

Backfill permeability requirements will depend on the general hydrologic environment and depository design geometry. Consideration of all these factors is part of a long-term risk analysis which is beyond the scope of this study.

However, it is possible to state what effect different depository environments and designs will have on the backfill permeability requirements.

Conditions Which Will Permit Use of Higher Permeability Backfill - The following conditions will serve to reduce the need for impermeable backfills:

- Reliable shaft and borehole seals
- Absence of significant permeable geologic faults intersecting waste storage rooms
- Depositories in effectively impermeable formations (possibly salt) with storage rooms which are hydrologic dead-ends
- Absence of upward hydraulic gradients.

Conditions Which Will Make Low Permeability Backfill Desirable - The following conditions will make the use of a low permeability backfill more important.

- Unreliable shaft and borehole seals
- Large upward hydraulic gradients
- Numerous geologic flaws
- Multiple poorly sealed shafts with an overlying aquifer which has significant horizontal hydraulic gradient.

In general, existence of one or more of these conditions suggests a need for backfill material with permeability of less than 10^{-8} cm/sec.

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Figure 5.3-1 shows the relative ranges of permeabilities for various backfill types. Low permeable plugs constructed at key locations within the depository would have

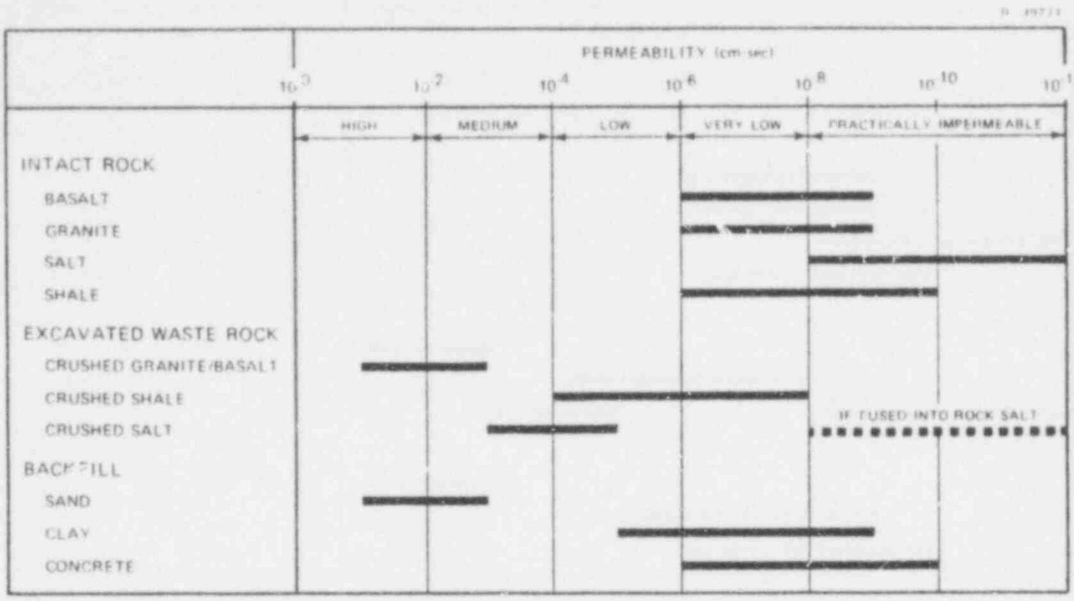

Figure 5.3-1 General Ranges in Permeability for Different Formations and Types of Backfills

an effect similar to filling all of the rooms with a slightly more permeable backfill. Thus, a 20-foot plug of 10^{-8} cm/sec material at the entrance to a 600-foot long room has hydrologic properties along the axis of the room similar to backfilling the entire room with 3×10^{-7} cm/sec material. Conversely, a 1-inch separation between the top of the fill and the roof in an 18-foot square room would be equivalent to increasing the overall permeability of an otherwise impermeable backfill to about 10 cm/sec (based on Ref. 34). Of course, in such a situation the flow would all tend to concentrate in the open space away from the waste canisters, which are in the floor.

The initial unsaturated porosity of the fill impacts the resaturation time. In general, the relationship appears to be linear. Thus, all other things being equal, a resaturation time of 1000 years for an initial unsaturated porosity of 20 percent would decrease to 50 years for a porosity of one percent. Figure 5.3-2 indicates the general range in the initial porosity for the various backfill types. The initial porosity of the fill will change with time as it is compressed due to deformation in the storage room. The resaturation time will, in general, be a complex function of the backfill permeability, porosity, and compressibility.

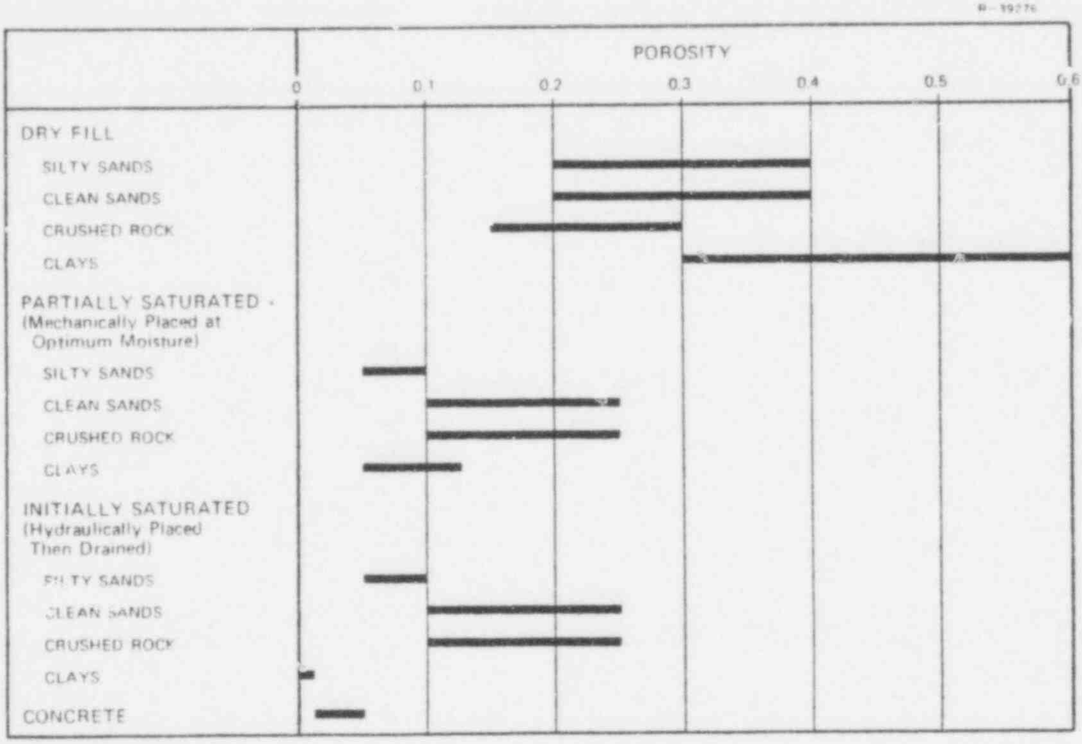

Figure 5.3-2 General Ranges in Porosity for Different Types of Fill

5.4 CHEMICAL AND THERMAL CONSIDERATIONS

In general, the chemical behavior of the backfill would form part of the overall effectiveness of the backfill barrier, but would probably not be critical. Optimum chemical and thermal characteristics include:

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- High Nuclide Retardation: High nuclide retardation would significantly reduce the effective permeability of the backfill to many nuclide species.

- Low Solubility: Low backfill solubility adds significantly to the credible life of the backfill and eliminates the risk of the backfill solutioning scenario.

- High Expansion Potential: A backfill which will absorb water and expand will provide a tighter contact between fill and depository openings.

- Chemical Stability: A chemically stable backfill will add to the credible life of the backfill.

- Noncorrosive: A backfill which does not produce any corrosive solutions with the potential groundwater inflows may increase the longevity of the waste form.

- High Thermal Conductivity: A backfill with high thermal conductivity will reduce the maximum temperature developed in the waste canisters and in the backfill. However, preliminary analyses (see Appendix A) indicate this effect would be very minor.

- Thermal Stability: A backfill which is thermally stable for the predicted 200 to 300°F temperature ranges will add to the credible life of the backfill and eliminate potential problems due to thermally-produced water.

5.5 SUMMARY

Requirements for the performance of backfill in a high-level waste repository have been discussed. The areas of concern include the structural, hydrologic, chemical, and thermal performance of the backfill material.

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It is concluded that the backfill should not be used to stabilize the pillars supporting the depository. Furthermore the structural advantages of using a dense fill over a compressible fill may be minor, particularly for adequately designed pillars and narrow rooms. It is suggested thatthe structural performance of the backfill be modeled to better predict the potential long-term deformations around the depository.

Backfill permeability should be less than about 10^{-8} cm/sec in cases where backfill permeability may be critical. Where the backfill provides an additional and not important barrier to waste release a permeability less than about 10^{-6} cm/sec is recommended. Positioning of low permeability plugs can significantly reduce the requirements of backfill permeability.

A backfill which interacts chemically with the waste to retard its transport may be very advantageous. Backfills such as clays are known to reduce the transport velocity of some radionuclides by as much as 10^6.

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6. CONCLUSIONS

6.1 POTENTIAL DECOMMISSIONING SCHEMES

It is not possible to recommend specific decommissioning schemes until specific sites are selected and the long-term risk evaluations are complete. However, the general characteristics of an adequate decommissioning scheme will probably include:

- High Quality Shaft Seals: In most situations, the shaft seal will be the critical engineered element in depository decommissioning. Thus, the seal should be designed with a high degree of conservatism and carefully constructed. It should effectively seal both the shaft openings and any associated fracture zones. Use of multi-element seals should be considered, since they provide a higher degree of safety. The seal must be composed of nonsoluble material.

- Low Permeability Backfill: It will probably be necessary to provide a low permeability seal along the axis of the depository, to minimize both the effects of operational problems and long-term risk scenarios. This could be accomplished through the use of either a low permeable plug at critical locations or a low permeable backfill. The low permeability backfill would probably consist of a clay or shale, possibly mixed with sand or waste rock to facilitate placement and/or reduce costs. The plugs would probably consist of concrete, compacted clay mixtures, and/or a bitumen mixture. With the use of plugs it may be acceptable to use relatively permeable backfill such as crushed waste rock as the primary backfill material.

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- Sealing of Fracture Zones: It will probably be necessary to provide for sealing of potential pathways through the roof fracture zone in the depository openings. Due to the problems of the long-term stability of the roof (see Section 5.2), it will probably not be practical to seal all the existing and potential long-term fractures along all the openings. Thus, a fracture grouting procedure in conjunction with the depository plugs is recommended.

- Structural Support: It will probably be necessary to backfill all the depository openings in order to minimize the potential long-term deformation. As discussed in Section 5.2, the practical backfill materials will minimize, but cannot by themselves eliminate deformation. Pending additional detailed deformation modeling, it appears that the stiffness and placement of the backfill are not critical. Thus, the use of the crushed waste rock would be adequate for the structural support requirements.

- Sequence: In the early stages of the repository, prior to placement of any waste, it may be desirable to construct a test backfilling and/or plug section to confirm the design concept. It may also be desirable to decommission sections of the depository after the waste is placed. This would reduce the potential impact of operational accidents and provide relatively long-term (30 years) monitoring of the backfill during the repository operations phase. This option would have to be weighed against the increased problem of retrieving waste, if necessary, in backfilled rooms.

6.2 SUGGESTED FUTURE WORK

There are several topics that need further study to better define decommissioning requirements. These include:

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- Incorporation of the results of long-term risk analyses into the decommissioning requirements

- Modeling of deformation behavior around depository openings with and without fill (see Section 5.2)

- Evaluation and testing of the concept that crushed salt under pressure will fuse into massive rock salt

- Evaluation of long-term structural and chemical integrity of concrete, grouts, asphalt, and other potential sealing and plugging material

- Evaluation of schemes involving liquid backfilling (see Section 3.7)

- Potential effects of operational disaster scenarios which may prevent or inhibit proper decommissioning

- Comparing the advantages of backfilling and sealing the storage rooms as the waste is placed to the disadvantages related to retrievability

- Evaluation of underground equipment removal or burial and decontamination of shafts prior to sealing.

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APPENDIX A
POST-DECOMMISSIONING THERMAL ANALYSIS

A.1 METHOD OF ANALYSIS

The repository storage rooms will be backfilled as part of the decommissioning process. This appendix describes simulations of the time-temperature histories for the backfilled repository. The simulations were performed with the HEATING5 computer code using a modification of the thermal model that was discussed in Volume 4. The modification in the model is necessary because the only heat transfer process in the backfilled storage room is conduction through the backfilling material. Hence, radiative and convective heat transfer in the room are eliminated from the backfill thermal model. The temperatures at the time of backfilling are given by the time-temperature histories reported in Volume 4. A cross section of the storage room, waste package, and salt pillar is shown in Fig. A.1-1.

There are four initial assumptions concerning the backfill operation:

- The repository will be backfilled either 5 years or 25 years after w[illegible]e emplacement
- The backfilling material will be crushed salt
- The temperature of the crushed salt used to backfill will be 70°F

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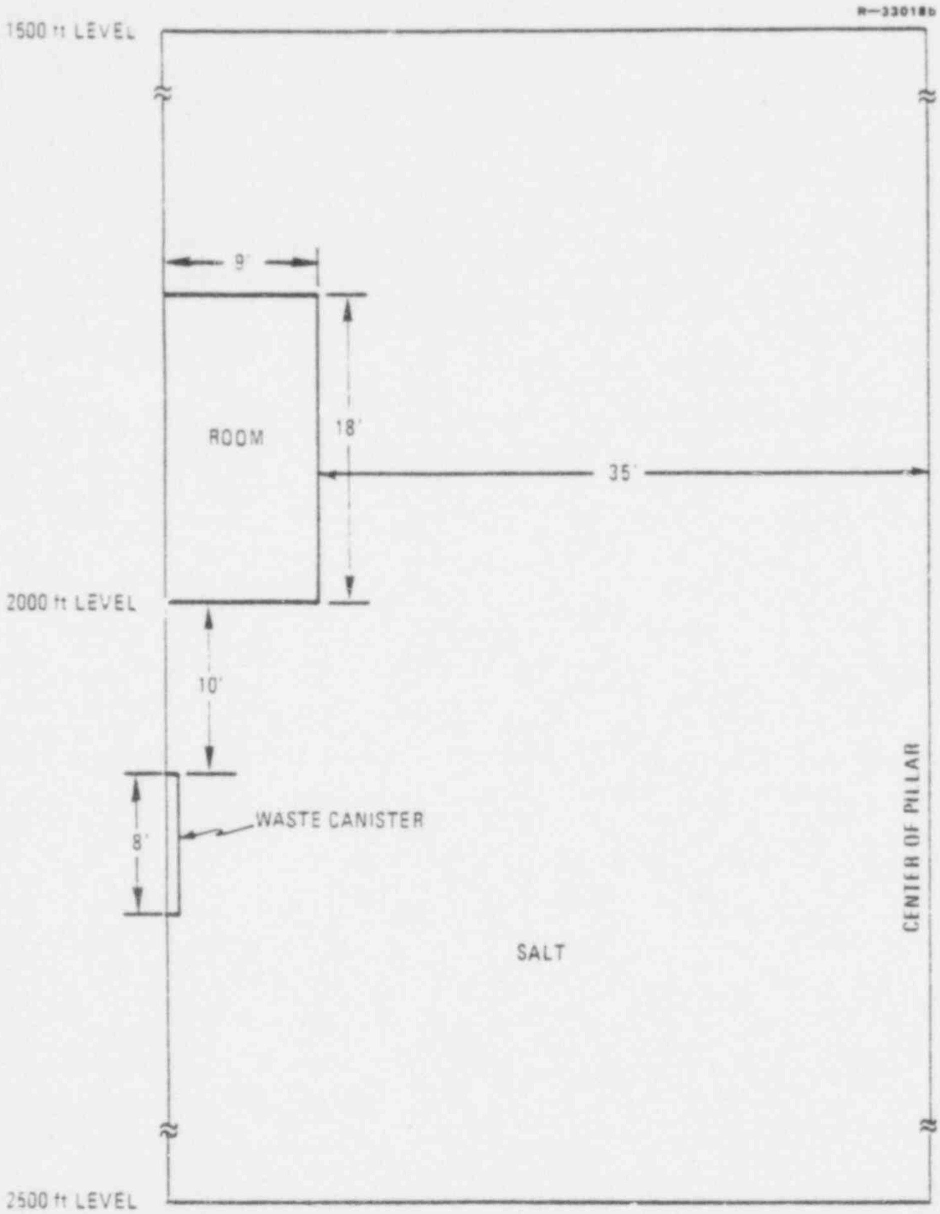

Figure A.1-1 Repository Cross Section

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- The backfilling operation can be performed so that the crushed salt completely fills the storage room.

The thermal properties of crushed salt are given in Ref. 35 as:

- Thermal Conductivity: 0.13 Btu/hr-ft-^{O}F
- Density: 108 lb/ft^3
- Specific Heat: 0.2 Btu/lb-^{O}F

Because of uncertainty as to the structural stability of repositories with 40 ft pillars (Volume 4), only 70 ft pillar widths were considered. The two cases simulated give the highest and lowest pillar temperatures. In the first the salt is assumed to have a low conductivity and the depository has not been ventilated (see Volume 3). In the second case the salt conductivity is high and the depository has been ventilated. In the following, the terms "ventilated" and "unventilated" will refer to the condition of the repository prior to backfilling.

A.2 TEMPERATURES IN A BACKFILLED HIGH-LEVEL WASTE REPOSITORY

Unventilated Cases - The simulated temperatures for a repository that is backfilled at 5 years are illustrated in Fig. A.2-1 which shows the temporal variation of the peak floor, ceiling, and pillar centerline temperatures. A thermal loading of 100 kW/acre was assumed. The floor temperatures rise sharply and the ceiling temperatures fall sharply immediately after backfilling because the thermal resistance of the backfilled room is about 100 times greater than that of the unventilated storage rooms. The pillar temperatures are only 10^{O}F higher than for the unsealed

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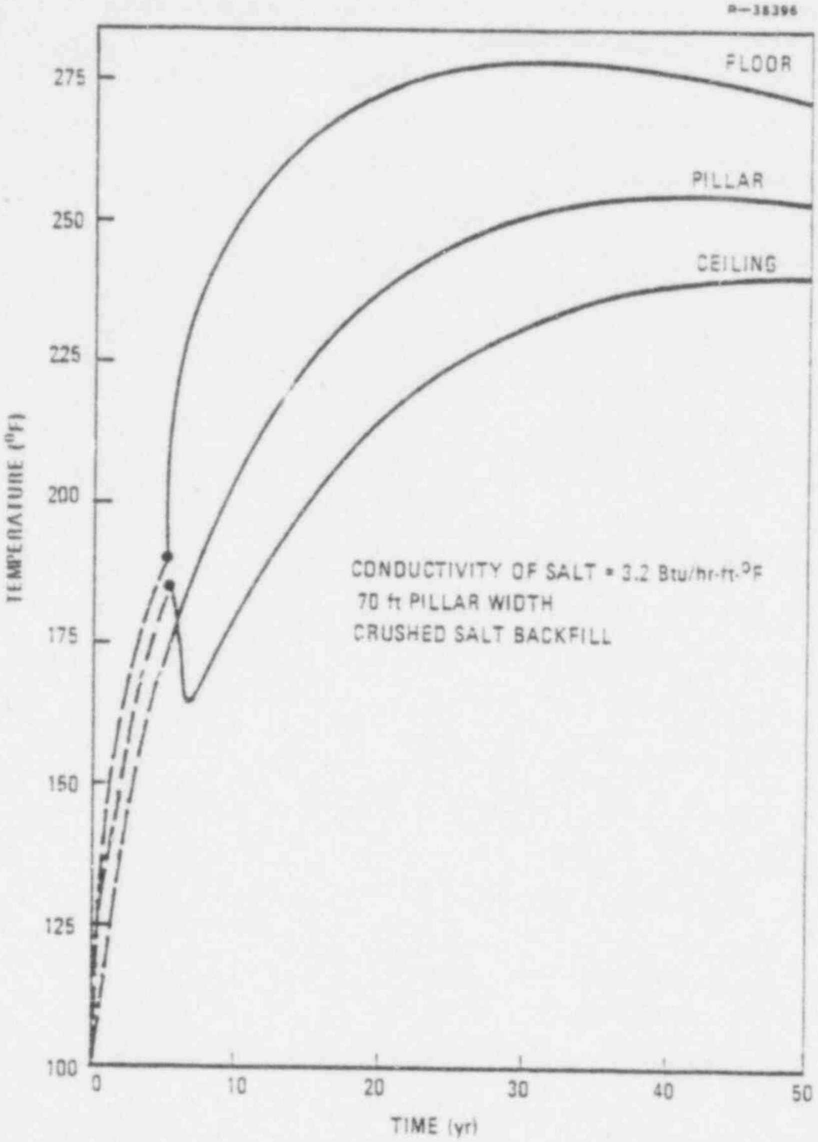

Figure A.2-1 Peak Temperature in a Backfilled Unventilated Repository

room. This temperature rise results from increased horizontal heat flow caused by the thermal resistance of the crushed salt.

Results for the unventilated repository backfilled after 25 years were qualitatively similar.

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Ventilated Cases - Figures A.2-2 and A.2-3 show the peak floor and pillar centerline temperatures for the ventilated repositories and for backfilling at both 5 and 25 years. In these figures, the dashed lines indicate the temperatures of the repositories without backfill while the solid lines show temperatures for backfilled repositories. The difference in temperatures between ventilated repositories backfilled at 5 and at 25 years is substantial.

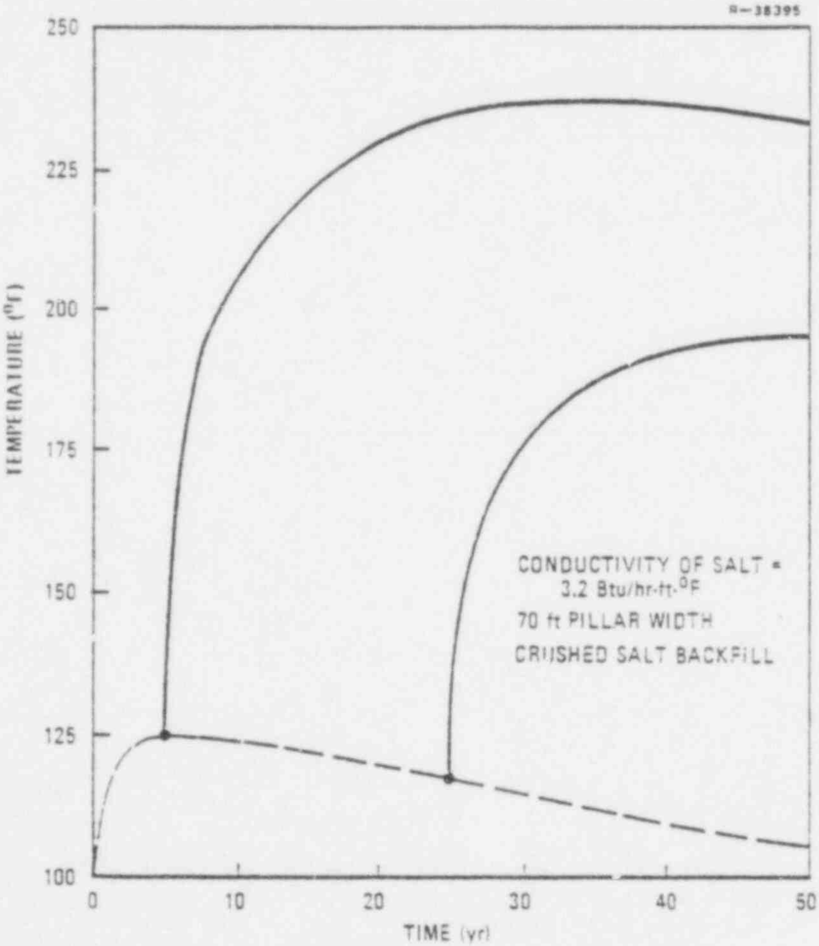

Figure A.2-2 Peak Floor Temperature for a Backfilled Ventilated Repository

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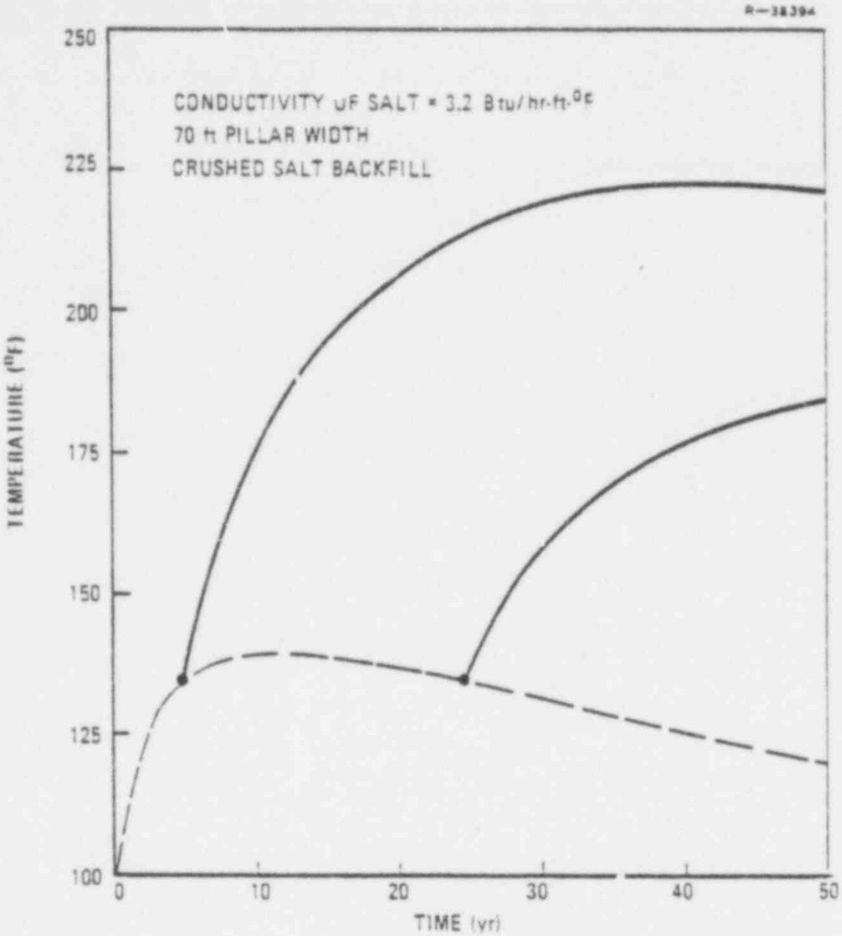

Figure A.2-3 Peak Pillar Centerline Temperature for a Backfilled Ventilated Repository

A.3 SENSITIVITY OF THE RESULTS

The sensitivity of the simulated temperatures to changes in the backfill scenario were studied. In one case, crushed salt was replaced as the backfill material by concrete with the thermal properties (Ref. 36):

- Thermal Conductivity: 0.54 Btu/hr-ft-^{o}F
- Density: 144 lb/ft^3
- Specific Heat: 0.2 Btu/lb-^{o}F

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In another case, insufficient crushed salt was assumed to have been used to fill the room. Consequently, a 0.5 ft gap was modeled between the top of the crushed salt and the ceiling of the room. Heat transfer by natural convection and radiation across the gap were included in the model. In neither case were the temperatures reported in Section A.2 changed by more than $3^{o}F$.

Spent Fuel - The temperatures in a ventilated spent fuel repository which was backfilled after five years were also simulated. The thermal model used was a version of the model given in Volume 3 that was modified to include the backfill material. The thermal loading assumed was 50 kW/acre. A further modification of the model was to assume adiabatic boundaries at the top and bottom of the unit cell. This was done because the temperature simulations were continued to 100 years after emplacement.

The simulated peak pillar centerline temperatures for the spent fuel repository are shown in Fig. A.3-1. Note that the highest pillar temperature does not occur until about 75 years after emplacement -- considerably later than with reprocessed high-level waste.

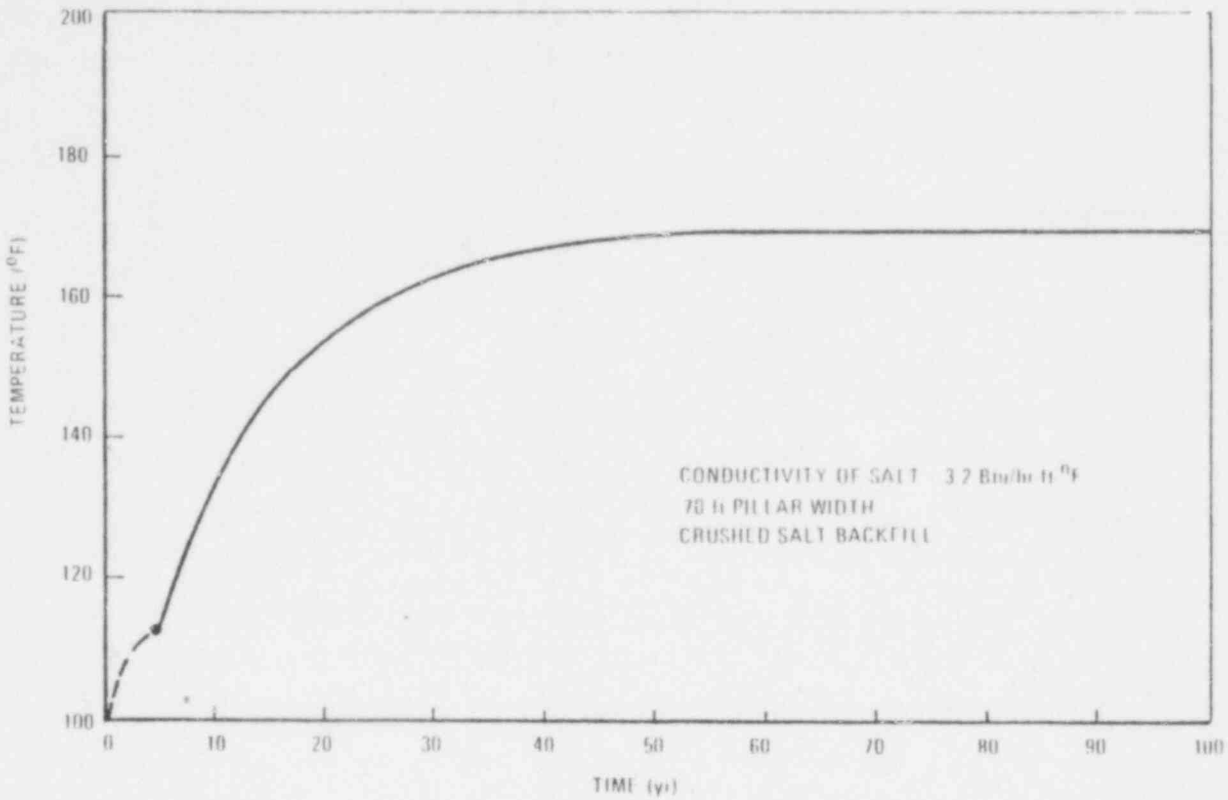

Figure A.3-1 Peak Pillar Centerline Temperature in a Backfilled Ventilated Spent Fuel Repository

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1843 051

GLOSSARY

Abutment: a surface or mass provided to withstand thrust; as in the end supports of an arch. The outer limits of the depository or the shaft pillars are examples of abutments.

Alteration: any change in the mineralogic composition of a rock brought about by physical or chemical means.

Anhydrite: a mineral consisting of anhydrous calcium sulfate.

Apparent Elastic Limit: that stress at which the rate of deformation is 50 percent greater than the initial rate of deformation.

Applied Deviatoric Loading: the net stress experienced by an element of rock under triaxial loading conditions, equal to the difference between the applied normal stress and the confining pressure.

Aquiclude: a zone which will store water but does not transmit significant amounts.

Aquifer: zone below the surface of the earth which will store water and also produce substantial amounts (as through a well).

Argillaceous: term applied to all rocks composed predominantly of clay minerals such as slate, shale, etc.

Artesian: refers to groundwater under sufficient hydrostatic pressure to rise above the aquifer containing it when unconfined.

Auger: a rock drill in which the cuttings are continuously, mechanically removed from the hole bottom without the use of fluids.

Backfill: sand, crushed rock, or other material used to fill voids in underground openings.

Bedded: refers to rocks resulting from consolidated sediments and exhibiting planes of separation between depositional units.

Benching: a process by which an excavation is enlarged by drilling and blasting vertical holes in the floor.

Bentonite: a soft, plastic, porous rock consisting largely of colloidal silica and composed essentially of montmorillonite clay minerals.

Biaxial Stress: a state of stress in which one of the principal stresses is zero.

Bitumen: natural inflammable substances composed principally of a mixture of hydrocarbons -- i.e., petroleum, asphalt, etc.

Blasting: the operation of breaking rock by boring a hole, inserting an explosive charge, and detonating the charge.

Blind Drilling: drilling of a large diamete hole without the use of a small, predrilled pilot hole.

Borehole: a hole drilled into soil or rock to obtain geologic and hydrologic information.

Breasting: process of enlarging an excavation by drilling horizontal holes in the roof parallel to the excavation.

Breccia Pipe: zone of angular fragmented rock.

Bulkhead: a tight partition of wood, rock, or concrete used to seal underground openings.

Burn Cut: a technique used in blasting underground where the cut holes are drilled parallel to the excavation, one or more holes being left unloaded.

Cable Tool Drill: a drilling machine based on the percussive principle in which the rock at the bottom of the hole is broken up by the drill bit chipping the rock with a series of repeated blows.

Calyx Drilling: a method of rotary core drilling using a toothed, hardened steel cutting bit.

Caving: fracturing of the rock overlying an underground excavation as it collapses into the excavation.

Clastic Rock: a consolidated sedimentary rock composed of broken fragments that are derived from preexisting rocks and that have been transported individually for some distance from their place of origin.

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Closure: reduction in dimension of an underground excavation through deformation.

Cohesion: the cohesion of a rock or soil is that part of the shear strength which does not depend upon interparticle pressure.

Compressive Strength: the load per unit area at which an element of rock will fail, or rupture.

Confining Pressure: a pressure applied perpendicular to the major direction of loading.

Constitutive Equations: equations relating stress to strain whose character depends upon the physical properties of the material under consideration.

Continuous Mining: a mining method where a mining machine mechanically breaks the rock and loads it onto either conveyor belts or haulage truck in one operation.

Contour Blasting: shaping the walls of an excavation by special blasting.

Convergence: see closure.

Core: cylindrical sample of rock obtained by drilling.

Creep: slow deformation in rock that results from the application of constant stress.

Cushion Blasting: a method of blasting in which the hole is substantially larger in diameter than the cartridge.

Cut-and-Fill: a method of underground mining whereby ore is removed overhead in a series of horizontal slices or cuts, working from a lower to an upper level, each cut being sequentially backfilled.

Decrepitation: the breaking up of a mineral, usually violently, when heated.

Depository: a subterranean cavern excavated in a deep geologic medium for the disposal of nuclear waste.

Deviator Stress: the difference between the major principal stress and the minor principal stress.

Dike: a tabular body of igneous rock that cuts across the structure of adjacent rocks, usually resulting from igneous intrusion.

1843 054

Dilation: the volume expansion of a fracture during shearing processes.

Dip: the angle at which a planar feature is inclined to the horizontal.

Dip Direction: the bearing of the maximum dip line of a planar feature.

Discontinuity: a fracture, fault or other change in rock mass.

Dolomite: a common rock-forming mineral, $CaMg(CO_3)_2$.

Downcast: the shaft through which fresh air is forced into the mine.

Drilling Mud: a viscous fluid containing bentonite or equivalent materials used in drilling rock to improve efficiency, reduce damage to in situ rock, and control subsurface gas and water pressures.

Effective Porosity: the portion of the pore space in a saturated permeable material in which flow of water takes place.

Effective Stress: the difference between the rock stress and the pore water pressure.

Elastic Modulus: the slope of a line describing the recoverable strain as a linear function of stress.

Evaporite: a non-clastic sedimentary rock composed of minerals produced from a water body that became concentrated by evaporation.

Extraction Ratio: the ratio of the area or volume mined to the total area or volume.

Face: the solid surface of unbroken rock at the advancing end of an excavation in progress.

Fault: a fracture or fracture zone along which displacement of the sides relative to one another has occurred.

Fissile: term applied to bedding consisting of thin laminations.

Forced Convection: heat transfer as a result of the forced passage of a fluid over a heated surface.

Friction Angle: a measure of the shear force necessary to overcome the shear resistance of a rock due to interparticle pressure.

1843 055

Free or Natural Convection: the motion of a fluid due to density changes arising from heating.

Full Face Blasting: excavating the entire face of the advancing excavation in a single phase operation.

Geophone: a detector, placed on or in the ground, which responds to ground motion at the point of its location.

Grout: a thin paste (usually cement) used to fill fractures underground either to increase structural support or decrease permeability.

Halite: rock salt, NaCl.

Head: height to which a fluid will rise above a base elevation due to the pressure in the fluid.

Headframe: the shaft hoisting frame and associated equipment at the top of a shaft.

Horizon: a particular stratigraphic level in the geologic column.

Hydrostatic Pressure: a condition wherein the pressure is equal in all directions.

Hygroscopic: readily taking up and retaining moisture.

Interbed: a bed of one kind of rock material occurring between or alternating with beds of another kind.

Invarient: a mathematic combination of stress (or strains) acting on an infinitesimal particle that is not directionally dependent and has a constant value.

Joint: fracture in rock along which no movement has occurred.

Kneading and Static Compaction: alternative standard methods of compacting soil samples for testing and quality control in soil construction.

Limiting Equilibrium Technique. an analysis method which determines the minimum strength parameters necessary for stability of a structure by analyzing the structure at the moment of failure.

Lithology: the physical characteristics of a rock.

Logging: the recording of information obtained from drilling.

Longwall: a method of underground mining whereby virtually all of a rock seam is extracted and the roof is allowed to cave uniformly behind an advancing mining front.

Massive Rock: competent rock that has a homogeneous structure over wide areas free from minor joints, layering, or similar features.

Mixed Convection: heat transfer when the processes of free and forced convection are comparable.

Mylonite: a fine grained laminated rock formed by the grinding of rock and fault surfaces during movement along the fault.

Negative Crystal: a hollow opening shaped like a crystal presumably formed by the solution of a previously existing crystal.

Normal Stiffness: a measure of the deformation characteristics of a joint in a rock, defined as the increase in normal stress force that results from each unit increment of normal displacement.

Normal Stress: the component of stress perpendicular to a given plane, either tensile or compressive.

Octahedral Shearing Strain: the shear strains associated with the octahedral shearing stress.

Octahedral Shearing Stress: the shear stress across a plane equally inclined to the principal stress axis, which is a function of the second invariant of the principal stress deviations; used as a yield criterion for plastic materials.

Open Stoping: a method of mining in which the walls and/or roof of the stopes are supported by rock pillars.

Overburden: rock or soil that overlies a potential excavation.

Packer: a device lowered into a borehole that can be made to expand to produce a watertight joint against the sides of the borehole.

Parting: a thin layer of material dividing mineral veins or beds.

Peak Strength: the maximum stress that can be applied to a rock in compression before it fails.

1843 057

Percussive Drill: see cable tool drill.

Permeability: a measure of the capacity of a rock for transmitting a particular fluid. Also referred to as the hydraulic conductivity. The term permeability is often used in a different sense to describe the capacity of rock for transmitting fluid independent of fluid density and viscosity. The former definition was used in these volumes.

Piezometer: a device for measuring in situ water pressure.

Pillar: a vertical column of rock left in an underground excavation, usually to support the roof.

Plastic: behavior in which a material is capable of deforming indefinitely and permanently under a constant stress.

Plug: a zone of normally impervious material placed in an excavation so as to prevent the flow of water.

Pneumatic Backfilling: placing fill with a high velocity air stream.

Poisson's Ratio: the ratio of lateral expansion to the associated longitudinal contraction in a material under stress.

Polyhalite: a mineral, $K_2MgCa_2(SO_4)_4 2H_2O$.

Pore Pressure: the stress transmitted through the fluid that fills the voids between particles of rock.

Porosity: the ratio of the volume of voids in a rock or soil to its total volume.

Pozzolan: siliceous tuff, ash, or other material used in cement which when mixed with lime hardens under water.

Presplitting: used in blasting to form a fracture plane around the perimeter of an excavation.

Principal Stress: the stress acting on an infinitesimal particle can be resolved into three orthogonal planes on each of which the stress is uniquely normal and the shear stress is zero. These stresses are called the major, intermediate and minor principal stresses.

Raise Roring: the process of drilling large diameter holes between different mine levels by enlarging a pilot hole with a full-face drill bit.

Repository: the entire region, subterranean and surface, which will be owned by the Federal government for the purpose of HLW disposal.

Ripping: the act of breaking rock or soil by a steel toothed machine.

Room and Pillar: a method of underground mining in relatively flat lying deposits whereby a grid of rooms separated by rock pillars is excavated.

Rotary Drill: a drilling machine that rotates a drill bit attached to a rigid string of rods.

Rotary/Percussive Drill: a drilling machine which combines percussive drilling with bit rotation.

Scaling: the scraping down of loose rock from the roof or walls of an excavation.

Sedimentary: formed by the deposition of sediment.

Shaft: an excavation of limited area compared to its depth which provides access to underground mines and is used for hoisting men and materials or for ventilation.

Shaft Collar: the junction of a mine shaft and the ground surface.

Shear Stiffness: a measure of the deformation characteristics of a joint in rock, defined as the increase in shear stress force that is required to produce each unit increment of shear displacement.

Shear Strength: the amount of shear stress that can be sustained without failure.

Shear Stress: any of the tangential components of the stress tensor.

Shear Zone: a zone in which in situ shearing has occurred on a large scale so that the rock is visibly crushed.

Shotcrete: cement sprayed on tunnel walls as a thin lining to increase the structural stability of the opening and to decrease the loss of moisture from the rock.

Sill: an igneous intrusive body of rock emplaced parallel to the bedding or schistosity of the intruded rock.

1843 059

Slickenside: polished and striated surface resulting from frictional forces during movement along a fault plane.

Smooth Blasting: technique used in blasting to form a smooth wall during excavation by initiating the perimeter charges after the main charges are fired.

Spall: to break off in layers parallel to the surface.

Static Compaction: see kneading compaction.

Strain Hardening: material behavior whereby each additional increment of strain requires an additional increment of differential stress.

Stand-up Time: the length of time that an excavation will remain stable without support.

Stope: an underground excavation from which ore is extracted.

Stopping: a masonry or brick wall built across old mine workings used to control the ventilating air.

Strain: linear or volumetric deformation resulting from an applied stress; expressed as a percentage or fraction of the original length or volume.

Stratigraphy: the arrangement of strata as to geographic position and chronologic order of sequence.

Stress: the applied force divided by the area over which it is applied.

Strike: the direction or bearing of a horizontal line in a structural plane such as a fault, joint, or bedding plane.

Subsidence: the lowering of a part of the earth's surface, often due to the collapse of an underground opening or removal of fluids such as water, oil, etc.

Sump: a surface excavation or diked area to hold water, drilling mud, sludge, and discharged matter from drilling.

Sylvite: a white or colorless isometric mineral, KCl.

Tailings: fine ground rock, formed as a waste product from ore beneficiation processes.

Tangential Stress: shear stress.

Tectonic: pertaining to the deformation of the earth's crust. Usually associated with earthquakes and volcanic activity.

Tensile Strength: the maximum amount of stress which can be applied to a rock in tension.

Tensile Stress: a normal stress that tends to cause separation across the plane on which it acts.

Tension: stress that tends to pull a body apart.

Trackless Mine: a mine in which rail haulage is not used. In these mines, rubber tired vehicles or conveyor belts are used for haulage and transport.

Triaxial Strength: the strength of a piece of rock which is confined either by an external force or by adjacent rock.

Triaxial Stress Conditions: a situation in which none of the principal stresses is zero.

Tuff: a rock formed of small volcanic fragments.

Ultimate Strength: the maximum differential stress that can be sustained before failure.

Undercut: a technique used in underground blasting where a machine cut is made along floor level to provide a free face to which the rock can break.

Uniaxial Strength: the strength of a piece of rock loaded in one direction only and unconfined in all other directions.

Upcast: a shaft through which exhaust mine air is removed from the mine.

Viscoelastic: behavior of material where an applied stress produces some recoverable and some nonrecoverable deformation.

Void Ratio: the ratio of the volume of voids to the volume of solids in a material.

Volumetric Strain: the net change in volume resulting from an applied stress.

Vug: any opening in a rock, from the size of a small pea upwards.

Wedge Cut: a technique used in blasting where the central cut holes are drilled so as to break out a wedge-shaped section.

Yield Strength: the maximum stress which can be applied to a material before the material ceases to behave elastically.

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This report discusses the requirements for decommissioning a deep underground facility for the disposal of radioactive waste. The techniques for sealing the mined excavations are presented and an information base on potential backfill materials is provided. Possible requirements for monitoring the site are discussed. The performance requirements for backfill materials are outlined. The advantages and disadvantages of each sealing method are stated.

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