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Preconceptual Systems And Equipment For Plugging Of Man-Made Accesses To A Repository In Basalt

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Prepared for the United States
Department of Energy
Under Contract DE-AC06-77RL01030

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by

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September 1980

Prepared for Rockwell Hanford Operations
A Prime Contractor to U.S. Department of Energy,
Under Contract Number DE-AC06-77RL01030

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ACKNOWLEDGMENTS

The authors wish to acknowledge the support and contributions to the study made by members of the Rockwell Hanford Operations Engineered barriers group, including Don Brown, Dr. Mike Smith, Steve McCarel, and Dr. Floyd Hodges; Ray Mencken, Rockwell Hanford Operations Contracts Officer; and the professional direction and guidance given by Dr. Hans Ewoldsen of Woodward-Clyde Consultants. Dr. Ewoldsen recognized from the outset the chief problems faced in the performance of this project, and was uniquely able to organize and direct the diverse professional disciplines existing in Woodward-Clyde Consultants needed for the project. Among other Woodward-Clyde Consultants participants, special thanks and acknowledgment go to: Bob Green and Barbara Ranson, for engineering analysis; Perry Sioshansi and Gary Smith; for probabilistic and systems analysis; Simon Kisch, for machine and materials system analysis; Alberto Gomez-Masso, for computer model review; and Bill Black, Dave Gross, and Bernie Gordon, for judgmental evaluations of proposed plug systems. Peer review was performed at various stages by Bill Black, Dave Gross, Oliver Gilbert, Yoshi Moriwacki, and Mike Holloway.

The authors also wish to acknowledge and thank the members of the Technical Review Board for their considerable guidance and valuable advice in keeping this study on target. The Technical Review Board consisted of Doug Moorhouse, Ulrich Luscher, and Lloyd Cluff of Woodward-Clyde Consultants, Professor Jim Mitchell of the University of California at Berkeley, Professor Konrad Krauskopf of Stanford University, and Tyman Fikse of Fikse Engineering. Construction feasibility and cost studies were done in an expeditious and effective manner by F. P. Bystrowski and Company.

Finally, the authors are especially indebted to the WCC people who worked so hard to get all these data and conclusions into a useful, organized and professional-looking document, including: Heidi Horten, editor, Terrie Bullock and Rose Sayao, secretaries, and Leo Germano and his drafting staff.

0 EXECUTIVE SUMMARY

This report presents results of a study leading to preconceptual designs for plugging boreholes, shafts, and tunnels to a nuclear waste repository in basalt. Beginning design criteria include a list of preferred plug materials and plugging machines that were selected to suit the environmental conditions, and depths, diameters, and orientations of the accesses to a nuclear waste repository in the Columbia River basalts located in eastern Washington State. The environmental conditions are described in Appendix A.

The preferred materials, and the placement machines for those materials, are described in the beginning of this report. They were selected by Woodward-Clyde Consultants in an earlier phase of this same study (Taylor and others, 1979). These materials include both natural-occurring earth materials (basalt, smectite clays, clinoptilolite and various aggregates) and processed materials (portland cements, pozzolan and proprietary bentonites).

The completely natural materials are preferred because, in general, they can be proven to have existed in that state for geologic time, in stable condition, and in environments the same or similar to the basalt environment. Nevertheless, the processed materials have not been shown to be unstable in the limited geochemical test program performed as part of this overall study and reported elsewhere. Consequently, until other completely natural, stable, possibly self-cementing materials are identified, the chosen processed materials seem to be the best known material that can complement the natural materials for certain design purposes and that could adequately be placed in plug environments by available machines.

Availability is defined on a near term (5- to 10-year) basis. The choices of the presently most feasible machine and material combinations for borehole plugs are demonstrated in separate matrices in Figures 1 through 8 for each of the subenvironments of boreholes, shafts, and tunnels. Based on these matrices, preliminary sketches (presented in Figures 8 through 24), illustrate the proposed method of plug construction for the estimated feasible combinations of machines and materials. These methods are generally termed "Monolithic" Plug Schemes in this report because they usually describe the placement of a single type of material.

Next, a technical analysis of potential plug performance is developed. Seepage control criteria are emphasized as the most significant design function to be evaluated. The principal design criteria adopted include:

- Design life of 10,000 years (for purposes of analysis, a functional representation of an indeterminately longer containment period);

- Maximum seepage through the plug, after saturation, of 1 m^3/year (160 m pressure differential across the plug);

- Maximum credible radioactive waste leakage from the repository at one end of the plug must be reduced to proposed regulatory agency permissible levels at the other end of the plug;

- Plug must sustain a thermomechanical loading cycle from a 50°C change in temperature without compromising other performance criteria;

- Plug must have suitable bond strength to resist maximum credible axial forces (1,000 m of fluid pressure head).

Basic, idealized models conforming to theoretical mechanics and representative of expected loading conditions are analyzed separately, making possible closed-form solutions of the problem. Plug design parameters (e.g., depth of disturbance of the wall rock due to borehole excavation, altered wall rock permeability, required plug-wall rock permeability, and corresponding plug length) are obtained from solution of these idealized problems. These data are first approximations and are generally thought to be conservative. They are useful to provide criteria by which (1) to assess the strengths and weaknesses of the candidate plug schemes in their ability to meet the criteria; (2) to choose combinations of the monolithic plug elements for a number of multiple-zone plug schemes that are expected to have superior performance over the whole range of performance criteria; and (3) to compare all the schemes and to select the best ones for preconceptual design.

To accomplish the first task, all the performance criteria for a plug are sorted out into five basic design functions:

- Core barrier performance;

- Plug/wall rock interface performance;

- Support performance;

- Disturbed rock zone performance;
- Long-term integrity performance.

Plug schemes for each environment of boreholes, shafts, or tunnels are rated on their performance in three or more of these design functions, depending on the specific environment. Numerical ratings are assigned to each scheme for how well the plug is expected to perform in each of two to four design parameters that collectively made up the design function. For example, tunnel core barrier performance is made up of four design parameters: (1) ion exchange capability; (2) permeability, (3) uniformity of properties; and (4) unit cost (representative of construction difficulty). Within any design function, certain parameters are more essential to the acceptable performance of the function by the plug; within core barrier performance, permeability ratings are more important than cost ratings. An extended dominance analysis technique is used to work with these inequalities and to help identify the best plug schemes for each design function in each environment.

The listing of superior monolithic plug schemes for each design function is then the basis for assembling series of monolithic plugs into multiple zone plugs that have good performance over the entire set of design functions required for a borehole, shaft or tunnel (Figures 25 through 29).

The final task is to choose which are the best of the multiple zone plugs. At this stage, all the schemes are evaluated by a panel of professionals who have many years experience in geotechnical design and construction. The recommendations of the experts is then reviewed and synthesized with the technical analysis results, and three preconceptual designs for a borehole, shaft, and tunnel are developed. These designs are presented in Figures 80, 81, and 82.

The design for tunnels shows zones of concrete and mortared basalt blocks, interrupted at intervals along the length by seepage cutoff collars of a clay/sand slurry. The cutoff collars extend across the entire plug section and into the wall rock, through any disturbed rock zone (e.g., $K > 10^{-7}$ cm/sec in these analyses). The design for shafts shows zones of concrete and of compacted clay/sand mixtures. Seepage cutoff collars are used in the shaft also; they are concrete in this case and are contiguous with the concrete zone. Both tunnel and shaft designs presume the removal of any steel supports or linings (typically installed for construction purposes) before plugging. Metal construction linings needed in shafts might be left in place opposite high water flow aquifers within a plug design length, depending on special design criteria for constructing that plug interval. Borehole plug design includes alternately (1) a zone of pea gravel with a mixture of compressed bentonite pellets and bentonite slurry, and (2) a zone of cement grout. The zones are tremied in place. The nominal length for all plugs is 300 m, based on the interpretation of data in the technical analysis. Preconceptual instrumentation designs for the plugs are then developed (schematically shown in Figure 92).

Recommendations are made for work needed to strengthen and extend the analyses, results, and designs contained in the report. They include the need for an early, shallow borehole plugging test, the need for instrumentation data concerning the performance of large excavations in the basalt, and the need to investigate a wider range of potential failure modes, (such as creep failure of soft plugs, piping, plug solutioning, or dispersion).

1 INTRODUCTION

1.1 BACKGROUND

In 1976, the U.S. Department of Energy (DOE) initiated the National Waste Terminal Storage Program (NWTS). The Office of Waste Isolation at Oak Ridge National Laboratory was established to provide program management for the terminal storage program. In 1978, the functions of this office were superseded by the Office of Nuclear Waste Isolation (ONWI) at Battelle in Columbus, Ohio.

The objective of the NWTS is to provide multiple nuclear waste storage facilities in various deep geologic formations within the United States. The Columbia River basalts, which underlie a large portion of eastern Washington State and adjacent portions of Oregon and Idaho in the Pacific Northwest, were identified as a possible repository rock. Rockwell Hanford Operations (Rockwell) has the responsibility of investigating these basalts as a potential site for terminal storage of commercial nuclear waste. Within Rockwell, this study is called the Basalt Waste Isolation Project (BWIP).

In order to construct a subsurface repository in the basalt of the Columbia Plateau, man-made openings will be required for exploration, access shafts and tunnels, and storage areas. The diameters of these man-made openings, which are collectively referred to as boreholes, may range from 5 cm for existing vertical exploration holes to 6 or 7 m for shafts and tunnels (upper limits of 9 to 10 m are expected). When the repository is decommissioned, these boreholes will be sealed, or plugged, to preserve the integrity of the repository.

Woodward-Clyde Consultants (WCC) has been contracted to devise a plug system (materials, plug emplacement machines, placement techniques, and monitoring instrumentation) to seal boreholes, shafts, and tunnels leading to a radioactive waste repository 900 to 1,500 m below the plateau surface. The purpose of the plug system is to prevent the migration of harmful amounts of radioactive waste to the biosphere. To prevent this migration along man-made openings, it is likely that a variety of materials and series of multiple plug barriers will be used. The materials and plug system selected for the borehole plug must be compatible (stable) with the physical and chemical properties of the surrounding repository rock and its geologic environment. The materials considered include hard rock and noble metals, soil and portland cement concretes, natural cements, grouts, clay, sand, gravel, and mixtures of these. Each material or mixture of materials will contribute one or more favorable attributes to complement and preserve the integrity of the surrounding repository rock. The plug system will be emplaced by machines and techniques that will provide a suitable degree of confidence in the security and durability of the plug.

The WCC study consists of three tasks: Task I - Planning and Procurement; Task II - Testing and Preconceptual Systems; and Task III - Borehole Plugging Field Tests and Preconceptual Design of Plugging Systems. Initial Task I work was completed in fiscal year 1979 and is described by Taylor and others (1979). This report describes a portion of the Task II work for fiscal year 1979-1980. Additional Task II and Task III work is proposed for fiscal year 1980.

The objectives of the Task I study included: (1) the preparation of a preliminary list of candidate plug materials;

(2) a description of available machinery capable of placing candidate plug materials; and (3) the development of physical and geochemical testing programs to help evaluate the chemical stability and physical properties of candidate plug materials.

From the data developed during the Task I and II work, it is concluded to be feasible to design a plug system that will satisfactorily seal man-made openings leading to a nuclear waste repository in Columbia River basalt for significantly long periods of time (on the order of thousands of years). Work accomplished to date indicates that this plug system can be designed using both natural and processed materials and can be emplaced with existing placement machinery and modifications of that machinery. Other important conclusions are:

- Geochemical test data for candidate plug materials are interpreted to demonstrate compatibility with the chemical and physical properties of the plug environment;

- These candidate plug materials have characteristics that will tend to trap or otherwise inhibit the migration of radionuclides;

- Although gaps and uncertainties are present in existing data concerning the plug environment, enough parameters have been defined to initiate preconceptual plug design; and

- Geochemical and physical testing programs can be developed and used to help define potential plug behavior parameters in an initial laboratory simulation of the plug environment.

1.2 SCOPE OF WORK

The fiscal year 1979-1980 Task II work is presented in two parts: preliminary testing of materials for plugging of man-made accesses to a repository in basalt (described in a separate report); and preconceptual systems and equipment for plugging of man-made accesses to a repository in basalt (described in this report).

To fulfill the scope of the Task II work, WCC was requested to:

- Provide preconceptual systems for plugging boreholes, tunnels, and shafts in basalt;
- Describe preconceptual borehole plugging equipment for placing the selected materials in man-made accesses;
- Utilize the quality assurance program, program plan and schedule, and work plans previously developed for Task II; and
- Prepare a preliminary report.

The technical work was initiated by identifying the plugging schemes (for boreholes, shafts, and tunnels) for consideration. Using these schemes, numerical and probabilistic analysis of plug stability was conducted. Based on this analysis and the preliminary testing, preconceptual plugging systems were developed, and the placement equipment was identified.

Quality assurance and project management are considered indispensible parts of the this study because they provide a mechanism for conducting the program in a logical, traceable, and documented manner. The identification of required procedures, scheduling, and cost control were elements of quality assurance and project management. Monthly progress reports were made to Rockwell, and periodic progress meetings were held either at the WCC offices in San Francisco, California, or at the Rockwell offices in Richland, Washington. The progress of the program was also discussed and reviewed at two meetings of the Technical Review Board, which includes: Lloyd Cluff, WCC; Douglas Moorehouse, WCC; Dr. Ulrich Luscher, WCC; Dr. James Mitchell, University of California, Berkeley; Dr. Konrad Krauskopf, Stanford University; and Tyman Fikse, Fikse Engineering, Seattle, Washington. The program was also supplemented by telephone conversation between the WCC project manager and the technical liaison for Rockwell.

1.3 ORGANIZATION OF REPORT

The remaining sections of this report include: Chapter 2 - Preconceptual Schemes for Borehole Plugging; Chapter 3 - Analysis of Preconceptual Plugging Schemes; Chapter 4 - Preconceptual Plugging Systems; Chapter 5 - Limitations of the Present Study; Chapter 6 - Summary, Conclusions, and Recommendations; References; and Appendices A through G.

2 PRECONCEPTUAL SCHEMES FOR BOREHOLE PLUGGING

2.1 INTRODUCTION

An earlier report (Taylor and others, 1979) defined various candidate materials and candidate machines. The purpose of this section is to describe candidate borehole plugging schemes (i.e., which materials might be suitable for particular situations and which machines might be used to place them). This initial assessment is, to some degree, subjective and is based on experience and evaluation of research done by WCC and others in various aspects of this and other projects.

2.1.1 Objectives and Approaches

When developing preconceptual plugging schemes, an attempt was made to anticipate some of the generally known problem areas. (These problem areas are considered in more detail in later sections of this report dealing with problem definition and analysis techniques.) For example, rock undergoes stress changes and loosening for some finite distance back from the wall surface of an underground excavation. The amount of stress change and loosening is dependent on the diameter of the excavated opening, the physical properties of the rock mass, excavation methods, stress field, and other factors. Therefore, the plugging schemes presented in this report section include remedial grouting and excavation of cutoff collars along the plug length just prior to plugging. These measures are designed to mitigate possible seepage flows that would bypass the plug through the weakened wall rock.

Because of the problem of weakened wall rock, the difficulties of demonstrating complete effectiveness of any grouting cutoff scheme, and the possibility of damage to remedial measures due to subsidence above the repository excavation, vertical shafts that directly enter the repository may provide a more accessible flow path to the biosphere and thus are undesirable. The shaft should be excavated at some distance from the repository and should be connected to the repository by a tunnel. Consequently, even if the permeability of the wall rock could not be restored to its in-situ condition, the resistance to flow through and around a plug constructed in the tunnel and shaft could be greater than the resistance to flow through overhead, intact rock separating the repository and the biosphere. Thus, the in-situ condition would be the controlling factor in any analysis of seepage from the repository.

An initial assumption here is that small diameter boreholes do not cause significant stress change or loosening of surrounding rock and thus do not contribute to an increase in the in-situ permeability in the surrounding rock. Consequently, it may be acceptable to penetrate the proposed repository area with boreholes. Such a conclusion presupposes that the methods of plugging boreholes developed in this program are found to be satisfactory.

2.1.2 Preferred Candidate Materials

The following list of preferred candidate materials was identified in earlier studies (Taylor and others, 1979):

- Basalt;
- Smectite Clay, including Bentonite;
- Clinoptilolite;

- Portland Cement;
  - Type II and V
  - Pozzolan Portland Cement with Pozzolan
  - Portland Cement and Silica Flour
  - Chem Com Expansion Cements

- Aggregate (Hanford Site);
  - Gravel
  - Sand
  - Silt.

Certain additives, including aluminum powder and water-reducing admixtures (WRA), were also identified as being of potential use as a plug material.

2.1.3 Preferred Candidate Machines

The following list of preferred candidate machines was also described in an earlier report (Taylor and others, 1979):

- Tunnels
  - Small compactors for earth dams
  - Concrete pump systems
  - Heavy earth-dam-type equipment
  - Hammer drill or other small tampers mounted on a jumbo (mm)*

- Shafts
  - Small compactors for earth dams
  - Concrete wireline system
  - Concrete pump system
  - Pile-driving hammer-tampers (mm)*

---

*(mm) = machine modified for this study

- Boreholes
  - Oil and gas well gravel pack plant (mm)*
  - Rotary drilling, reverse circulation mud plant (mm)*
  - Grout pump system
  - Downhole hammer drill-tamper (mm)*
  - Tri-cone rock bit with earth rollers (mm)*

2.1.4 Materials Preparations and Mixtures

The actual plug materials may be a single material or a mixture of candidate materials combined to attain certain chemical and physical characteristics. Generalized mixtures or preparations of the materials being considered in physical property testing and preconceptual schemes are as follows:

Material	Material Components
75-mm maximum aggregate - in a stiff clay mixture - in concrete	Crushed basalt, zeolite, or other gravel; - alone or mixed with clay, silt, and sand; or - sand and cement.
10-mm maximum aggregate - in a stiff clay mixture - in a slurry clay mixture - in a cement mixture	Crushed basalt, zeolite, or other gravel; - alone or mixed with clay, silt, and sand; or - with sand and cement.

* (mm) = machine modified for this study

Clay mixed with sand and silt - pelleted (bentonite) - slurry	Bentonite, Ringold clay or other clay; - alone or mixed with cement; or - sand and silt.
Cement - slurry	Types II and V, pozzolanic and hydrothermal; - alone; or - with fine fillers.

2.1.5 Categories of Plug

An earlier report (Taylor and others, 1979) defines three categories of plug: those to go in boreholes, those in shafts, and those in tunnels. For the purposes of this report, this division has been further divided into subcategories. The new divisions are:

1) Boreholes Originating at the Surface - Holes not large enough for a man to get down and work in (a maximum of 1 m in diameter).

2) Shafts - Vertical holes large enough for a man to get into (larger than about 1 m in diameter; 1 m may be hazardous for deep situations, but actual shaft sizes are expected to be significantly larger).

3) Boreholes Originating Underground - Holes not large enough for a man to work in (about 0 to 1 m in diameter).

   a) Plug to be placed at a distance (greater than 3 m) from a large working area.

b) Plug to be placed near (about 0 to 3 m) a large working area.

4) Tunnels - Horizontal holes greater than about 1 m in diameter.

a) Small Tunnels - Tunnels in which it would not be practical to use heavy earth-moving equipment because of the lack of headroom (about 1 to 6 m in diameter).

b) Large Tunnels - Tunnels in which there is sufficient headroom to use heavy, earth-moving equipment (greater than 6 m in diameter but less than 10 m). The actual use of such equipment further depends on plug length:

- Large Tunnels Having Short Plugs - The use of heavy, earth-moving equipment is probably impractical for plugs less than about 25 m in length.

- Large Tunnels Having Long Plugs - Plugs which are long enough to warrant the use of heavy, earth-moving equipment.

These proposed subdivisions could present additional problems in machine selection and operating personnel safety and efficiency if opening sizes vary with the depths contemplated. It is expected that the actual sizes of the holes to be plugged will be narrower than those described above, with the anticipated range of sizes as follows:

Boreholes originating at surface:	50 mm to 600 mm in diameter
Shafts:	4.5 m to 8 m in diameter
Boreholes originating underground:	50 mm to 300 mm in diameter
Tunnels:	3 m to 10 m in diameter

2.1.6 Multiple-Zoned Plug and Materials Variations

It is possible that, in certain situations, multiple-zoned plugs will be used. A multiple-zoned plug is divided along the length of plug into separate zones of different types of material. The zones may change completely from one type of material to another (e.g., concrete to earth) or material in adjacent zones may be of similar type (e.g., earth, but of different physical properties, such as permeability and density). Such zoning is designed to make use of special properties of individual material types so that the overall performance of the zoned plug achieves all the design objectives of waste isolation plugs in basalt.

In the discussions that follow, each zone of a multiple plug will be considered as a separate individual plug. The material in that zone is essentially uniform along its length. Similar placement techniques are employed from one end of the plug to the other; however, some exceptions may occur in tunnel plugging where constricted working room for men and machines near the top or crown of the tunnel may make it desirable to reduce maximum sizes of material particles, such as the maximum size aggregate in concrete, and may require special types of machines for placement in the reduced space.

2.1.7 Linings

Tunnel or shaft linings, if used, may present problems during construction of the plugs. Linings of degradable material, such as steel, would probably have to be removed (except possibly where shafts cross aquifers) prior to plugging. Other linings, such as concrete, might be incorporated into the plug, if designed for plugging objectives and if suitably controlled during construction and undamaged during repository filling.

2.2 PLUG SYSTEMS

2.2.1 General

A major thrust of the project is to provide preconceptual designs for up to four plug systems that are estimated to be available on a near-term basis (5 years). The identification process for candidate schemes has consequently been weighted toward technologies where the necessary production machinery is commercially available and demonstrated on plug-like materials in operations similar to anticipated plugging operations. This methodology has thus far resulted in the "preferred" candidate machinery already described. It seems prudent, however, to continue a parallel identification, discussion, and evaluation of a category of plug systems that involve new research and development technologies. The most promising of these research and development (R&D) technologies might be useful for possible priority interest in future programs of the BWIP. Therefore , they will be included with the package of candidate schemes presented in this section.

2.2.2 Borehole Originating at the Surface

The plugs in these boreholes will frequently be placed at a distance from the ground surface. Therefore, the placing and compacting of materials, inspection of the plug, and quality control will be difficult. The system chosen to construct the plugs should preferably be one that has been shown by experiment and practical use to be capable of producing a plug of the necessary characteristics. The only available systems identified at present that partially meet this requirement are those used in the completion of deep oil and gas wells (i.e., the gravel pack and grout systems). Other conceptual schemes identified as being of potential use for compacted earth plugs also appear as candidates in this study. They are new concepts or are similar to concepts developed in earlier research in borehole plugging.

2.2.3 Shafts

The problems associated with non-slurry materials in boreholes are significantly reduced in shafts because of the increased size of shafts and the fact that men can get down to the plug locations to operate and repair equipment and to inspect the plug construction. Also, because of the increased size, compaction equipment that is presently available and has a proven record of providing suitable compaction can be used. An example of such equipment would be a hand-held power tamper. It is anticipated that the full range of preferred candidate materials could be used with the possible combinations of materials and machines shown in the accompanying matrices.

2.2.4 Borehole Originating Underground

2.2.4.1 Plug at a Distance from a Large Working Area

The problems associated with these boreholes will be similar to those encountered in the construction of plugs in boreholes originating at the surface. If the horizontal holes are inclined slightly downward, similar solutions to those used on surface holes can be employed. If the holes are inclined upward and a slurry mixture is selected, a packer would have to be used to prevent the slurry from running out of the hole.

2.2.4.2 Plug Near a Large Working Area

When boreholes do not extend long distances from man-sized work areas, a wider variety of materials and equipment can be utilized for plugging operations than is possible in boreholes that extend for long distances. Placing and compacting clayey material with a compactor attached to a tunnel jumbo represents just one such possible combination.

2.2.5 Tunnels

2.2.5.1 Small Tunnels

Small tunnels are those for which it would be impractical, due to lack of headroom, to employ large tractor-driven rollers for the compaction of earthen materials. In this case, earthen materials would be compacted with small, self-propelled or hand-held power tampers. Concrete-type materials could be used, and a medium size pump system would be employed. R&D work might demonstrate the feasibility of solid inclusion plugs, such as basalt and copper.

2.2.5.2 Large Tunnels with Short Plugs

The use of large rolling equipment is probably impractical for short, earthen plugs. These plugs, like those in small tunnels, could be constructed with small, hand-held power tampers. Again, concrete might be employed, or solid inclusion plugs might be feasible.

2.2.5.3 Large Tunnels with Long Plugs

For long plugs, large tractor-drawn rolling equipment could be used effectively to construct the lower part of an earth plug. The upper part of the plug could be constructed in the same way as a small tunnel by using self-propelled or hand-held power tampers. If concrete is selected as the plug material, a large-scale concrete pump could be used, or solid inclusion plugs might be feasible.

2.3 IDENTIFICATION OF CANDIDATE PLUGGING SCHEMES

Materials preparations and mixtures and candidate machines are shown in Figures 1 through 7 for each of the categories of plugs just discussed. The relative capability of each of the candidate machines to handle one or more of the materials preparations or mixtures appropriate for the matrix category of plug is subjectively evaluated. The reference literature of the project, professional experience, and engineering judgment are the basis for such identification.

The matrices match materials and machines for three levels of relative capability:

- Most feasible scheme (of those shown, but still requiring demonstration);

● Most-feasible scheme

○ Scheme considered possible at the time with little or no modifications

\+ Unproven scheme which would require extensive modification of existing equipment or design and demonstration of new equipment

MACHINE / MATERIAL	Oil and gas well gravel pack plant (d > 10 cm)		Rotary drilling reverse circulation mud plant (d > 10 cm)		Grouting system	Gravel packing plant	Down hole hammer drill (d > 10 cm)		Tri-cone rock bit (with earth rollers) (d > 10 cm)		R & D System (relevant sketch included)				Materials/Components
75-mm max aggregate															Crushed basalt, zeolite, or other gravel (alone or mixed with clay and sand or sand and cement)
- in stiff clayey mix							+		+						
- in concrete							+(1)								
10-mm max aggregate															Crushed basalt, zeolite, clay, sand, or other sand/gravels (alone or mixed with clay or cement)
- in stiff clayey mix							+		+		+				
- in slurry clay mix	○		○		●	●									
- in cement mix					●										
Clay - mixed with sand/silt							+		+		+				Bentonite and clay, possibly mixed with cement or sand/silt
- precompacted (bentonite)			○				+		+						
- slurry					●										
Cement															Types II and V, pozzolanic and hydrothermal (alone or with fine fillers)
- slurry					●										
Solid inclusion											+				Basalt, copper

NOTES: (1) Dry mix concrete

FIGURE 1

BOREHOLES DRILLED FROM THE SURFACE

● Most-feasible scheme

○ Scheme considered possible at the time with little or no modifications

\+ Unproven scheme which would require extensive modification of existing equipment or design and demonstration of new equipment

MACHINE / MATERIAL	Small compactors for earth dams (either self-propelled or hand held)		Concrete wireline system	Concrete pump system	Pile driving hammer/tampers	R & D System (see tunnel sketch)									Materials/Components
75-mm max aggregate															Crushed basalt, zeolite, or other gravel (alone or mixed with clay and sand or sand and cement)
- in stiff clayey mix					○										
- in concrete			●	●	○(1)										
10-mm max aggregate															Crushed basalt, zeolite, clay, sand, or other sand/gravels (alone or mixed with clay or cement)
- in stiff clayey mix	●				○										
- in slurry clay mix															
- in cement mix			●	●	○										
Clay - mixed with sand/silt	●				○										Bentonite and clay, possibly mixed with cement or sand/silt
- pelleted (bentonite)	●				○										
- slurry				●											
Cement															Types II and V, pozzolanic and hydrothermal (alone or with fine fillers)
- slurry				●											
Solid inclusion						●									Basalt

NOTES: (1) Dry mix concrete

FIGURE 2

SHAFTS

● Most-feasible scheme

○ Scheme considered possible at the time with little or no modifications

\+ Unproven scheme which would require extensive modification of existing equipment or design and demonstration of new equipment

MACHINE / MATERIAL	Oil and gas well gravel pack plant (d > 10 cm)		Grout pump system		Tri-cone rock bit (with earth rollers) (d > 10 cm)				R & D System (relevant sketch included)						Materials/Components
75-mm max aggregate															Crushed basalt, zeolite, or other gravel (alone or mixed with clay and sand or sand and cement)
- in stiff clayey mix															
- in concrete															
10-mm max aggregate															Crushed basalt, zeolite, clay, sand, or other sand/gravels (alone or mixed with clay or cement)
- in stiff clayey mix					+										
- in slurry clay mix	○		●												
- in cement mix			●												
Clay - mixed with sand/silt					+										Bentonite and clay, possibly mixed with cement or sand/silt
- pelleted (bentonite)					+										
- slurry			●												
Cement															Types II and V, pozzolanic and hydrothermal (alone or with fine fillers)
- slurry			●												
Solid inclusion									+						Basalt, copper

FIGURE 3

SUBSURFACE BOREHOLES (PLUG FAR FROM LARGE WORKING AREA)

● Most-feasible scheme

○ Scheme considered possible at the time with little or no modifications

\+ Unproven scheme which would require extensive modification of existing equipment or design and demonstration of new equipment

MACHINE / MATERIAL	Hand-held compactors attached to tunnel jumbo (includes hammer drills)		Concrete or grout pump system		Oil and gas well gravel pack plant				Tri-cone rock bit (with earth rollers)		R & D System (relevant sketch included)				Materials/Components
75-mm max aggregate															Crushed basalt, zeolite, or other gravel (alone or mixed with clay and sand or sand and cement)
- in stiff clayey mix															
- in concrete															
10-mm max aggregate															Crushed basalt, zeolite, clay, sand, or other sand/gravels (alone or mixed with clay or cement)
- in stiff clayey mix	○								+						
- in slurry clay mix			●		○(1)										
- in cement mix			●												
Clay - mixed with sand/silt	○								+						Bentonite and clay, possibly mixed with cement or sand/silt
- precompacted (bentonite)	○								+						
- slurry			●												
Cement															Types II and V, pozzolanic and hydrothermal (alone or with fine fillers)
- slurry			●												
Solid inclusion											●				Basalt, copper

NOTES: (1) Holes below horizontal

FIGURE 4

SUBSURFACE BOREHOLES (PLUG NEAR TO LARGE WORKING AREA)

● Most-feasible scheme

○ Scheme considered possible at the time with little or no modifications

\+ Unproven scheme which would require extensive modification of existing equipment or design and demonstration of new equipment

MACHINE / MATERIAL	Portable self-propelled or hand-held compactors				Hammer drill/tamper on jumbo (includes hand-held compactors on jumbo)		Handwork			Concrete pump system (large dam equipment)	Grout pump system			R & D System (relevant sketch included)	Materials/Components
75-mm max aggregate															Crushed basalt, zeolite, or other gravel (alone or mixed with clay and sand or sand and cement)
- in stiff clayey mix															
- in concrete										●					
10-mm max aggregate															Crushed basalt, zeolite, clay, sand, or other sand/gravels (alone or mixed with clay or cement)
- in stiff clayey mix	●				○										
- in slurry clay mix										●					
- in cement mix										●					
Clay - mixed with sand/silt	●				○										Bentonite and clay, possibly mixed with cement or sand/silt
- pelleted (bentonite)	●				○										
- slurry											●				
Cement															Types II and V, pozzolanic and hydrothermal (alone or with fine fillers)
- slurry											●				
Solid inclusion														+	Basalt
Basalt block with cement mortared joints							●								Basalt - cement mortar
Compressed bentonite blocks with dry pack joints							●								Compressed bentonite

FIGURE 5

SMALL TUNNEL

● Most-feasible scheme

○ Scheme considered possible at the time with little or no modifications

+ Unproven scheme which would require extensive modification of existing equipment or design and demonstration of new equipment

MACHINE / MATERIAL	Portable self-propelled and hand-held compactors			Hammer drill or hand-held compactor or jumbo	Handwork				Concrete pump system for tunnels	Grout pump system		R & D System (relevant sketch included)			Materials/Components
75-mm max aggregate															Crushed basalt, zeolite, or other gravel (alone or mixed with clay and sand or sand and cement)
- in stiff clayey mix															
- in concrete									●						
10-mm max aggregate															Crushed basalt, zeolite, clay, sand, or other sand/gravels (alone or mixed with clay or cement)
- in stiff clayey mix	●			○											
- in slurry clay mix									●						
- in cement mix									●						
Clay - mixed with sand/silt	●			○											Bentonite and clay, possibly mixed with cement or sand/silt
- pelleted (bentonite)	●			○											
- slurry										●					
Cement															Types II and V, pozzolanic and hydrothermal (alone or with fine fillers)
- slurry										●					
Solid inclusion												●			Basalt
Basalt blocks with cement mortared joints					●										Basalt-cement mortar
Compressed bentonite blocks with dry pack joints					●										Compressed bentonite

<u>FIGURE 6</u>

LARGE TUNNEL WITH SHORT PLUG

● Most-feasible scheme

○ Scheme considered possible at the time with little or no modifications

+ Unproven scheme which would require extensive modification of existing equipment or design and demonstration of new equipment

MACHINE / MATERIAL	Portable self-propelled and hand-held compactors	Large compactors		Hammer drill or hand-held compactors on tunnel jumbos		Handwork			Concrete pump system	Grout pump system			R & D System (relevant sketch included)		Materials/Components
75-mm max aggregate															Crushed basalt, zeolite, or other gravel (alone or mixed with clay and sand or sand and cement)
- in stiff clayey mix		●													
- in concrete									●(1)						
10-mm max aggregate															Crushed basalt, zeolite, clay, sand, or other sand/gravels (alone or mixed with clay or cement)
- in stiff clayey mix	●	●		○											
- in slurry clay mix									●(2)						
- in cement mix									●(1)						
Clay - mixed with sand/silt†	●	●		○											Bentonite and clay, possibly mixed with cement or sand/silt)
- pelleted (bentonite)	●			○											
- slurry										●(2)					
Cement															Types II and V, pozzolanic and hydrothermal (alone or with fine fillers)
- slurry										●(1)					
Solid inclusion													●		Basalt
Basalt blocks with cement mortared joints						●									Basalt - cement mortar
Compressed bentonite blocks with dry pack joints						●									Compressed bentonite

NOTES: (1) or (2) Designates one machine/material combination in a multiple machine machine/material requirement for the monolithic plug

FIGURE 7

LARGE TUNNEL WITH LONG PLUG

- Scheme considered possible at this time and having little or no modification; and

- Unproven scheme that would require extensive modification of existing equipment or design and demonstration of new equipment.

2.3.1 Summary of Available Plug Schemes

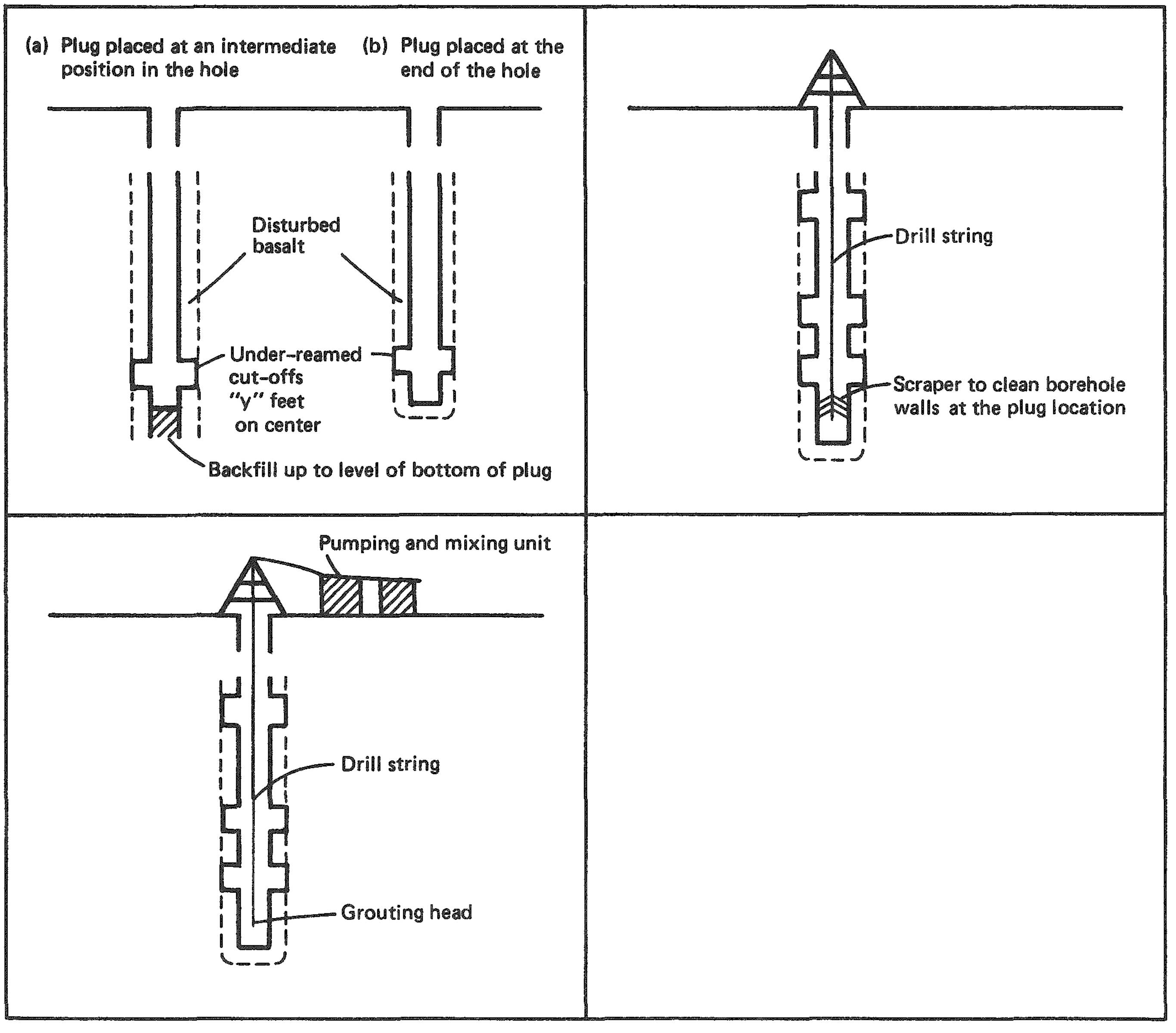
All of the schemes shown in the matrices and identified as "most-feasible schemes" or "scheme considered possible at this time with little or no modification" are considered available plug schemes. Plug systems representative of the third category of relative capability are considered R&D schemes. The available monolithic plug schemes can be simply categorized in machine and material combinations (detailed below and illustrated in Figures 8 to 24 along with R&D schemes; preconceptual multiple-zoned plug schemes are illustrated in Figures 25 to 29).

(1) Boreholes Originating at the Surface

Material	Placement System
(a) 10-mm aggregate in a clay slurry	Concrete pump
(b) 10-mm aggregate in a cement slurry	Concrete pump
(c) Cement slurry	Grout pump
(d) Clay slurry	Grout pump
(e) Clay slurry with or without pea gravel	Reverse or normal circulation mud

PLUG SYSTEM

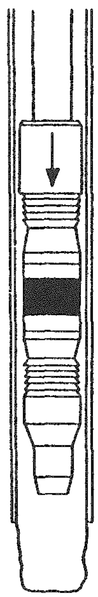
Materials	Equipment
10-mm aggregate in clay slurry 10-mm aggregate in cement slurry Clay slurry Cement slurry	Pumping equipment at surface Mixing equipment at surface



NOTE: Grouting sequence as shown on accompanying figure

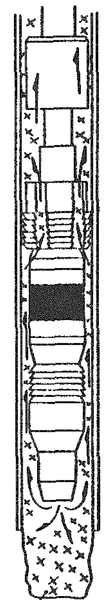
FIGURE 8

BOREHOLES DRILLED FROM THE SURFACE



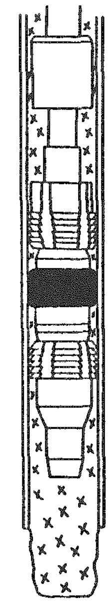
A

Cement retainer run down to the bottom of the hole



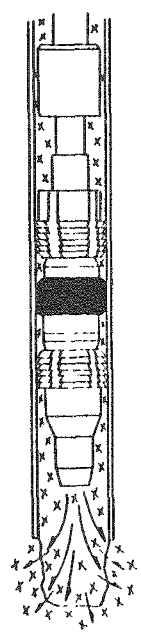
B

Grout pumped down and around retainer



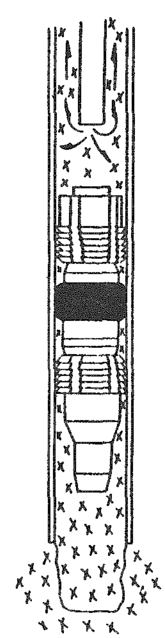
C

Retainer retracted to its final setting depth



D

Retainer set and the grout pressured into the rock fissures



E

Tubing removed leaving the retainer

FIGURE 9

THE USE OF A CEMENT RETAINER PLUG IN CASED HOLE

PLUG SYSTEM

Materials	Equipment
10-mm maximum aggregate in clay slurry mixture	Gravel-packing plant

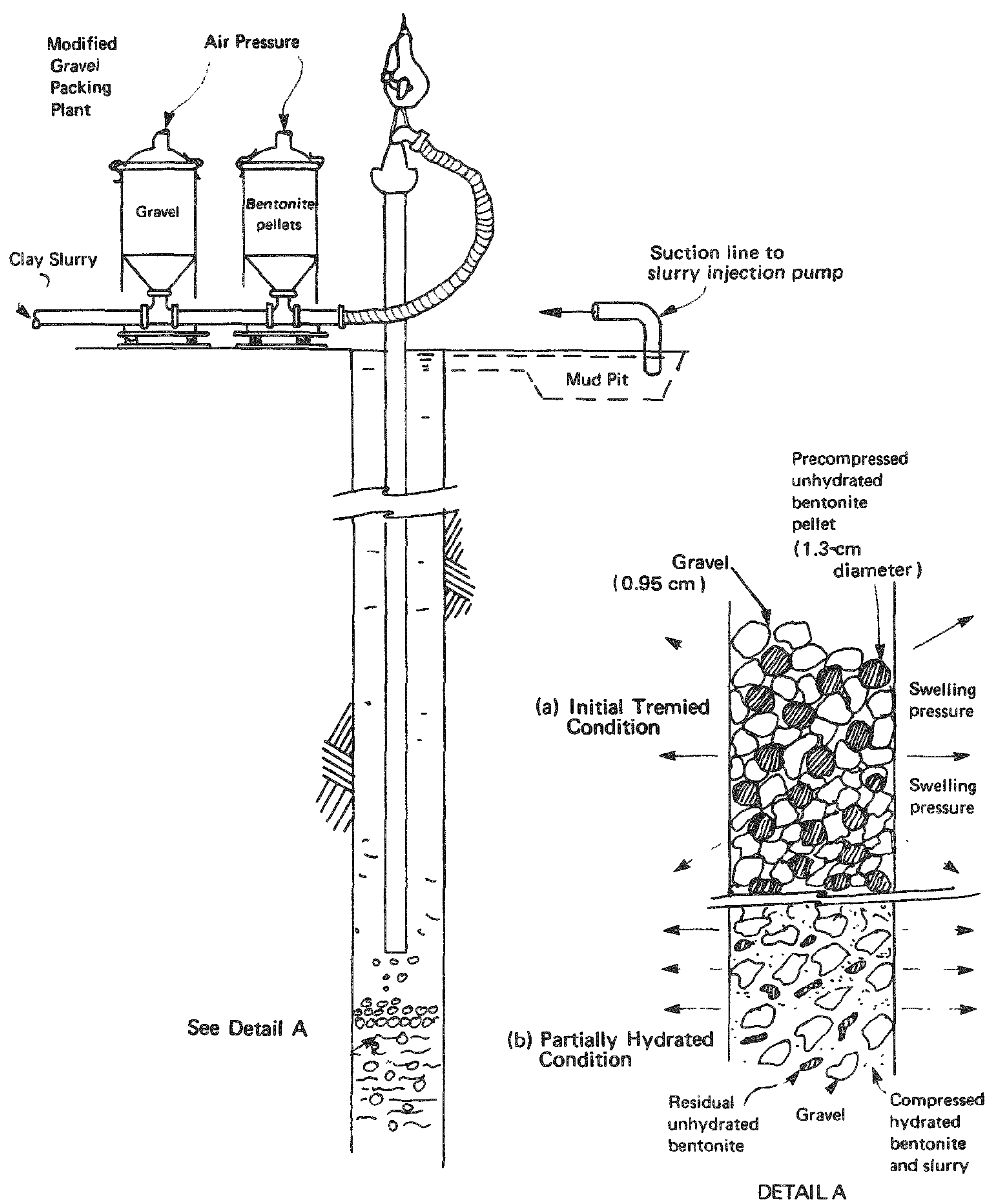


FIGURE 10

BOREHOLE PLUG OF PRECOMPRESSED BENTONITE PELLETS WITH GRAVEL PACK

PLUG SYSTEM

Materials	Equipment
10-mm aggregate with clay or bentonite slurry (possibly with compressed, dry bentonite pellets)	Reverse or normal circulation mud system - R & D concept

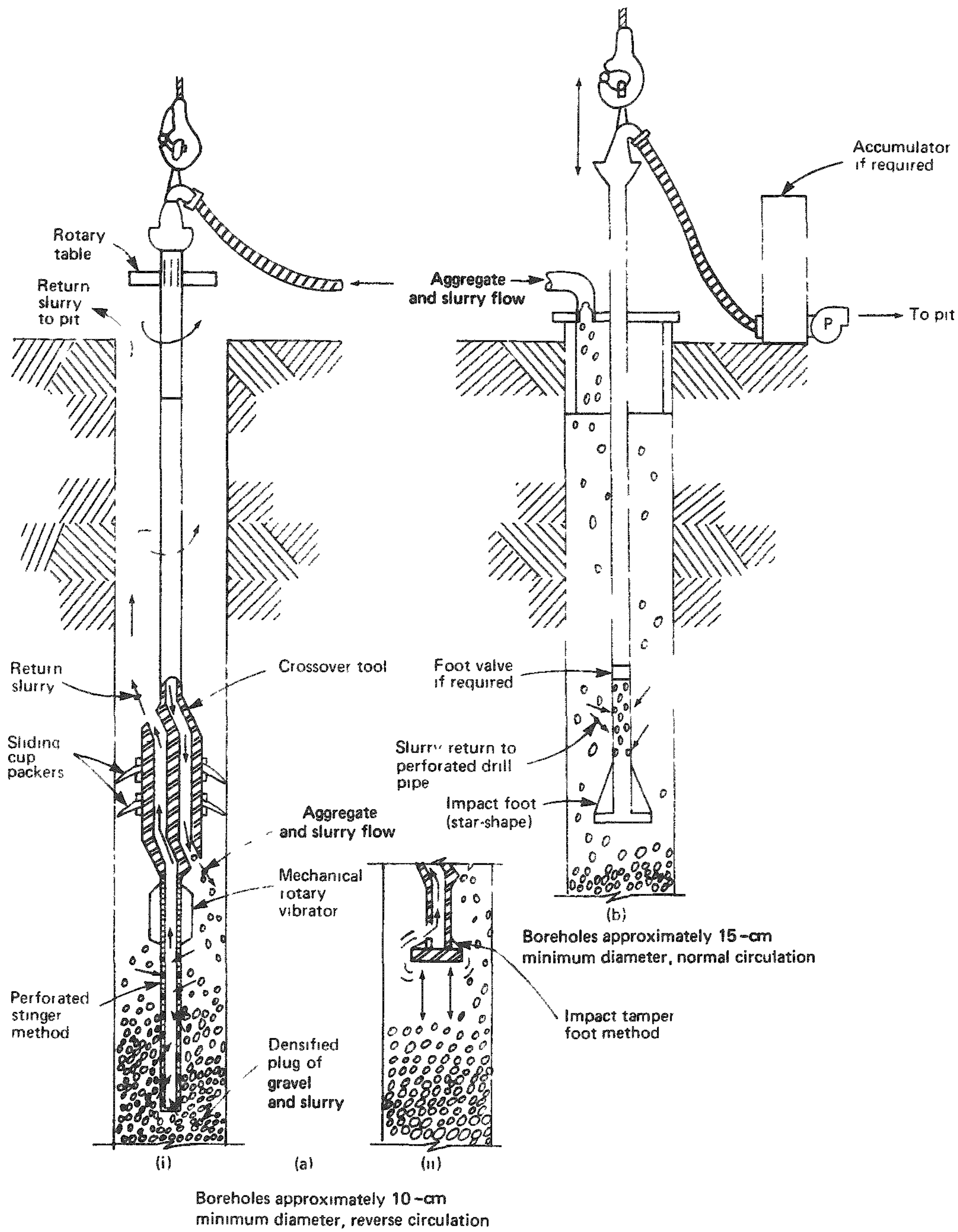


FIGURE 11

BOREHOLES FROM SURFACE

PLUG SYSTEM

Material	Equipment
Precompacted clay mixed with sand and silt	As shown - R & D concept

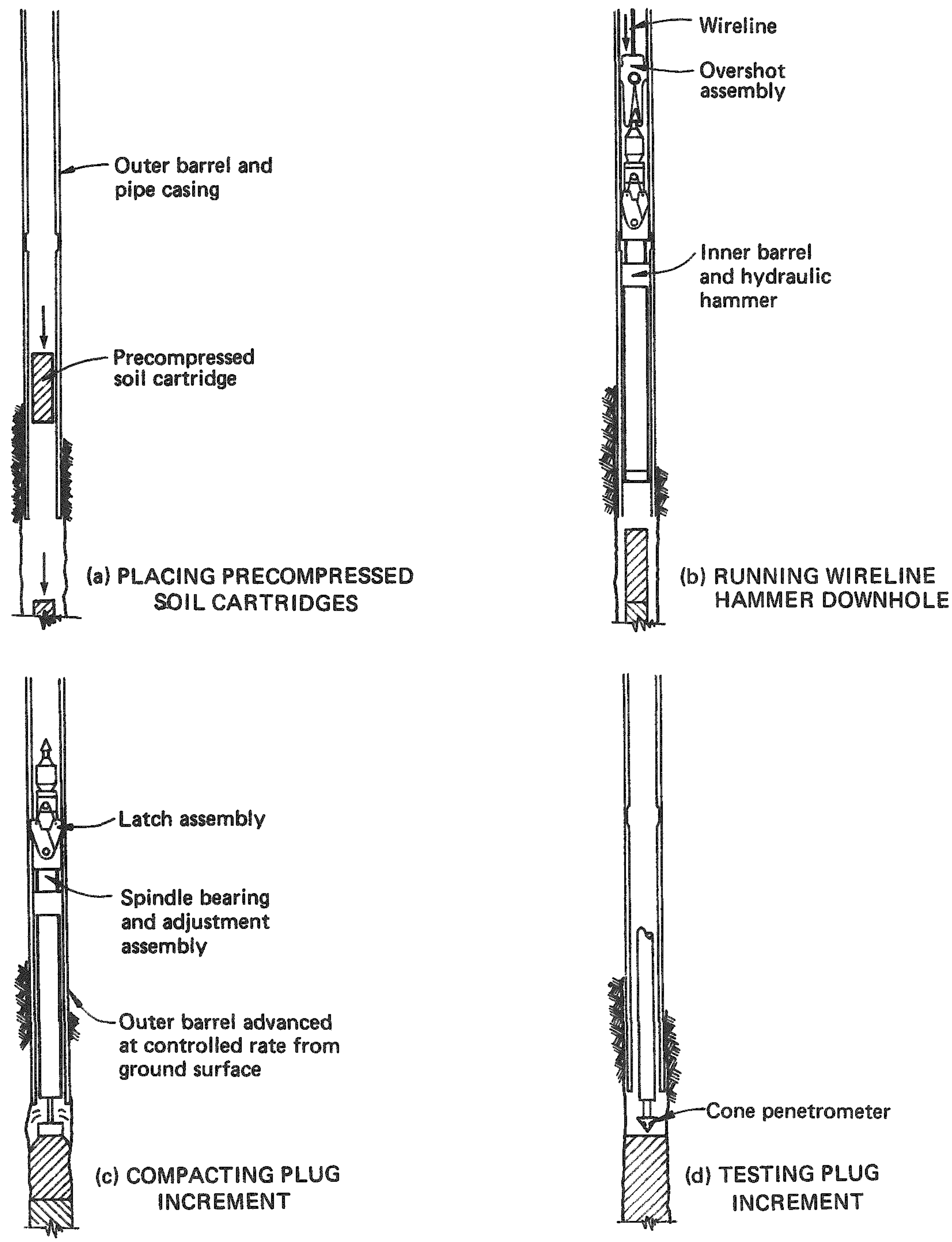


FIGURE 12

PRECOMPRESSED SOIL PLUG SCHEME FOR BOREHOLES

PLUG SYSTEM

Materials	Equipment
Precompacted copper powder and phosphorous	As shown - R & D concept

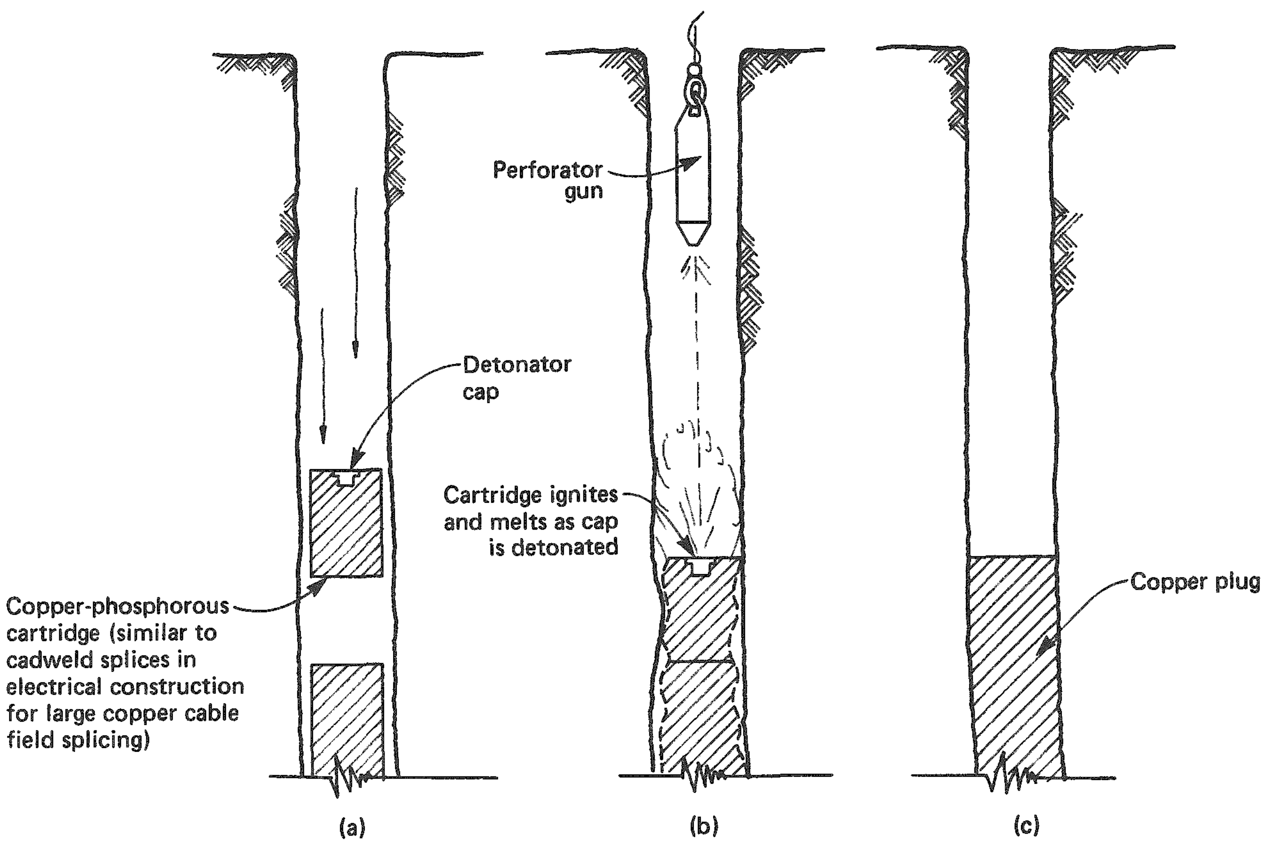
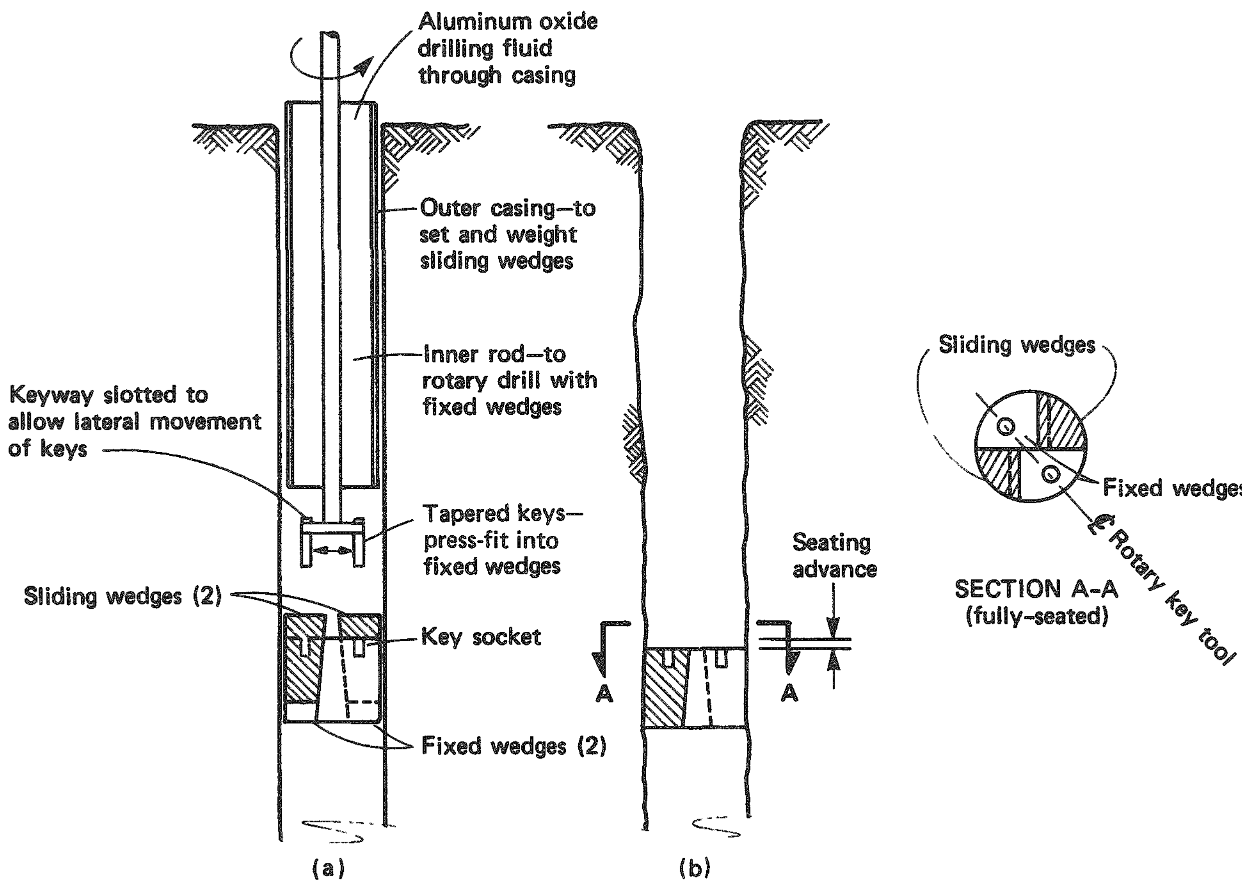


FIGURE 13

COPPER PLUG FOR BOREHOLES

PLUG SYSTEM

Materials	Equipment
Basalt	Rotary drill as shown, R & D concept



Exploded view of setting tools and plug; plug in retracted-diameter position.

Plug set and tools withdrawn, ready for inserting another plug in series.

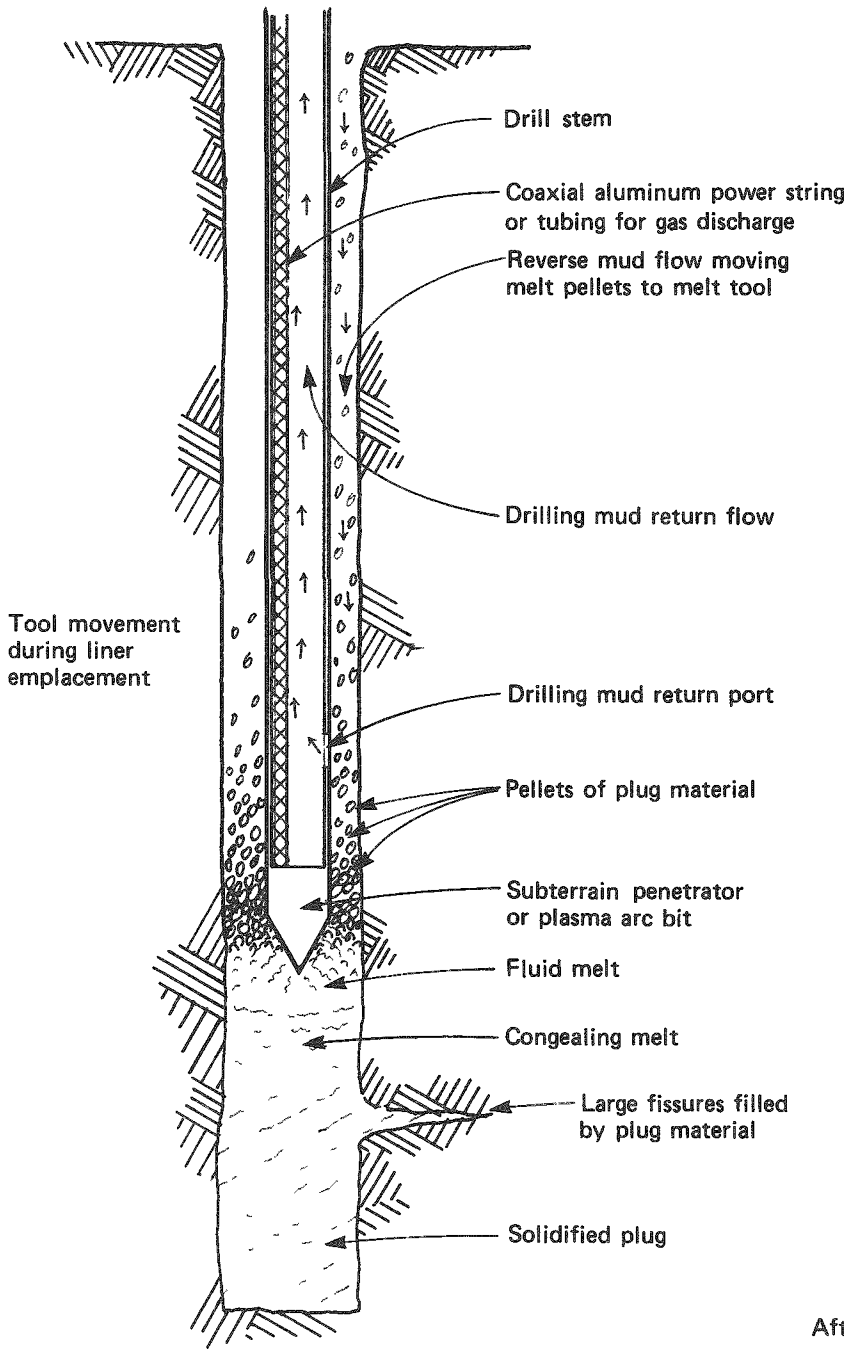
(wedges shown in section)

FIGURE 14

BASALT PLUG FOR BOREHOLES

PLUG SYSTEM

Materials	Equipment
Pelletized lead, lead alloys, or lead minerals; copper, salt, sulfur, natural glass, or basalt fragments.	As shown — R & D concept



After Altsheimer (1976)

FIGURE 15

CONTINUOUS MELT PLUG FOR BOREHOLES

PLUG SYSTEM

Materials	Equipment
Clay/sand mixture (with or without 10 mm aggregate pelleted bentonite)	Small compactors Working platform Wireline delivery system

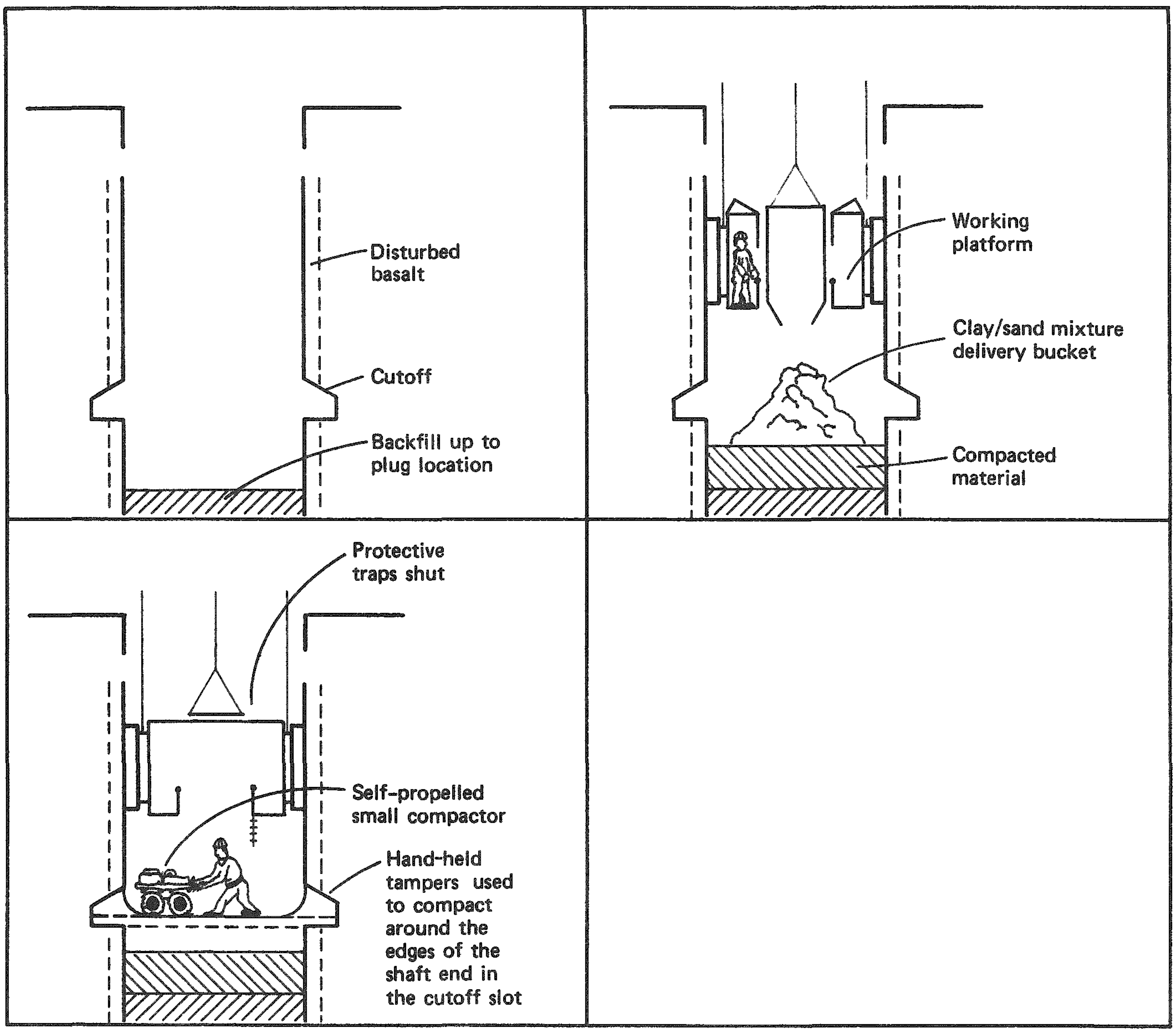


FIGURE 16

STIFF—CLAY/SAND PLUG FOR SHAFTS

PLUG SYSTEM

Materials	Equipment
Concrete with 75-mm or 10-mm aggregate	Concrete wireline system Working platform

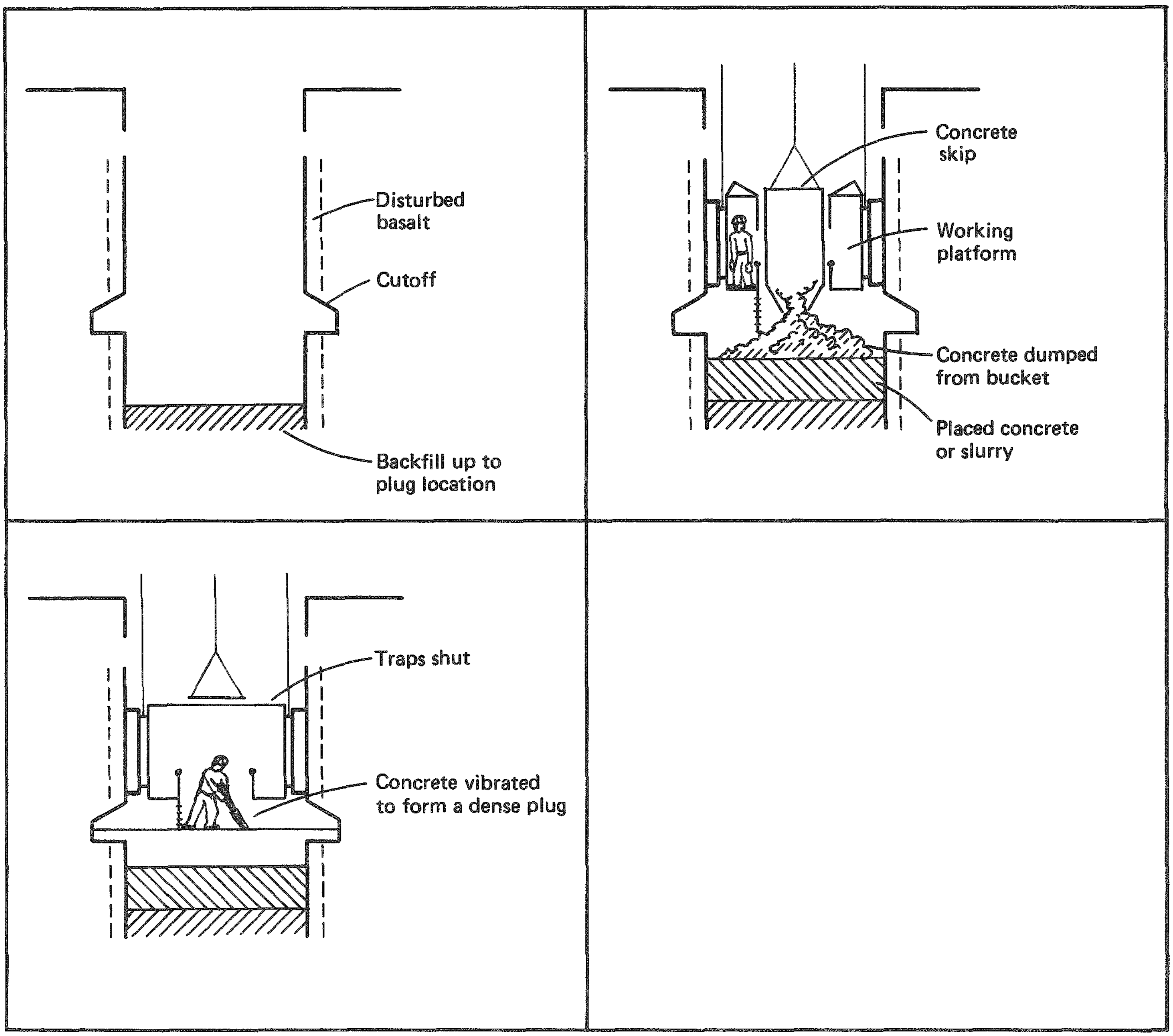
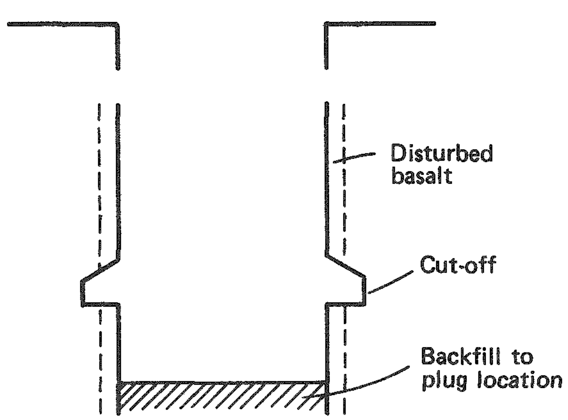


FIGURE 17

CONCRETE PLUG (1) FOR SHAFTS

PLUG SYSTEM

Materials	Equipment
75-mm or 10-mm aggregate concrete Cement slurry Clay slurry	Concrete pump Working platform



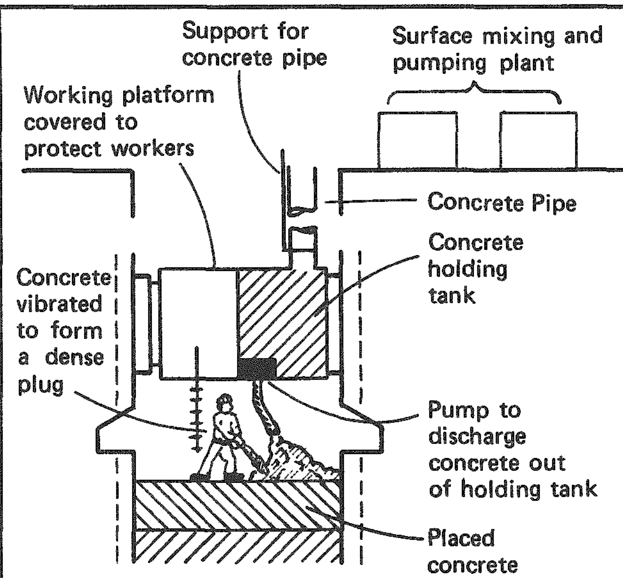


FIGURE 18

CONCRETE PLUG (2) FOR SHAFTS

PLUG SYSTEM

Materials	Equipment
Stiff clayey material, with or without 10-mm aggregate	Hand-held power compactor operated from tunnel jumbo, or horizontal hammer tamper as shown - R & D concept

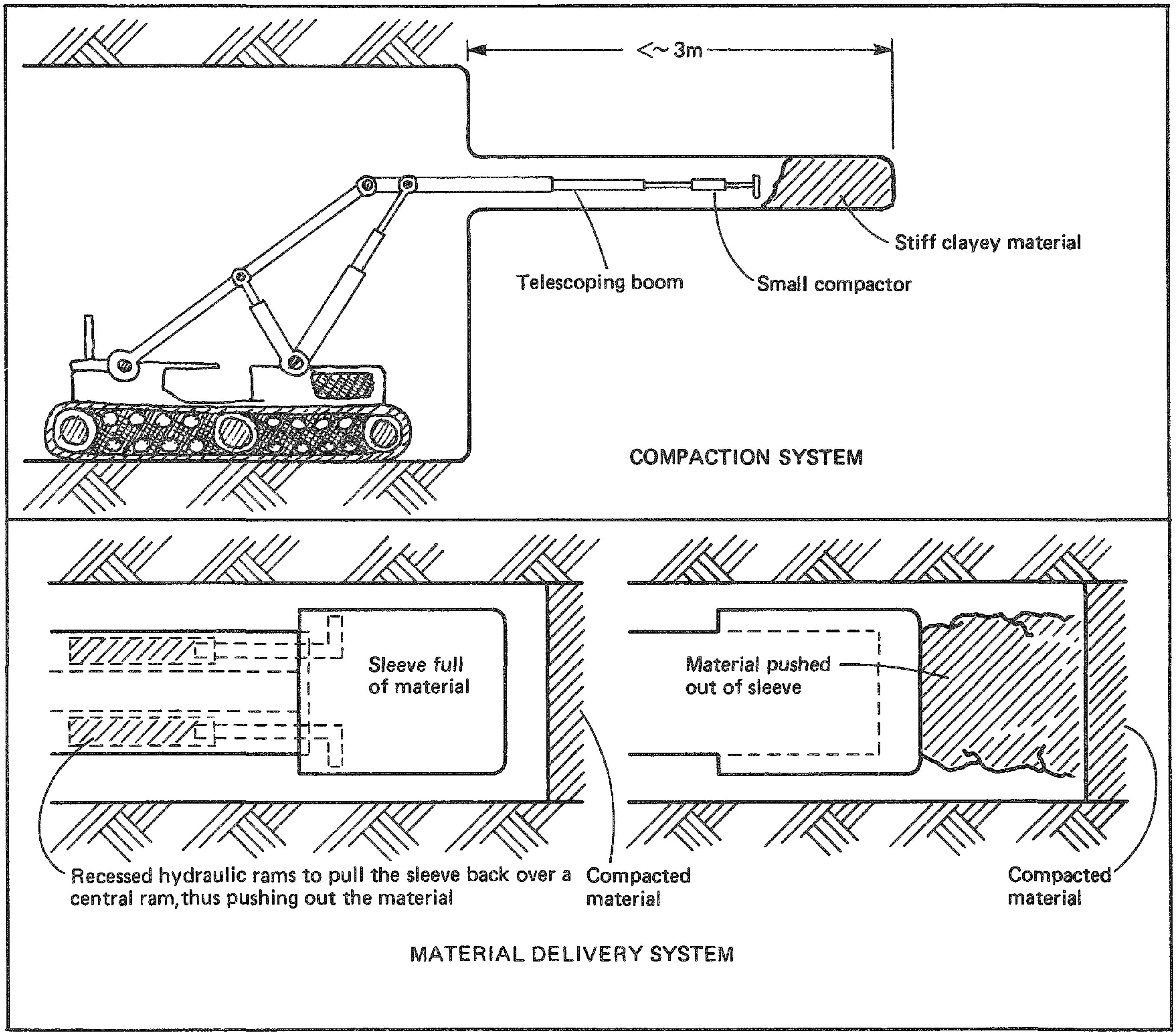


FIGURE 19

BOREHOLE ORIGINATING UNDERGROUND;
PLUG NEAR TO LARGE WORKING AREA

PLUG SYSTEM

Materials	Equipment
Stiff clays (with or without 10-mm aggregate) Bentonite pellets	Small compactors Material feed system

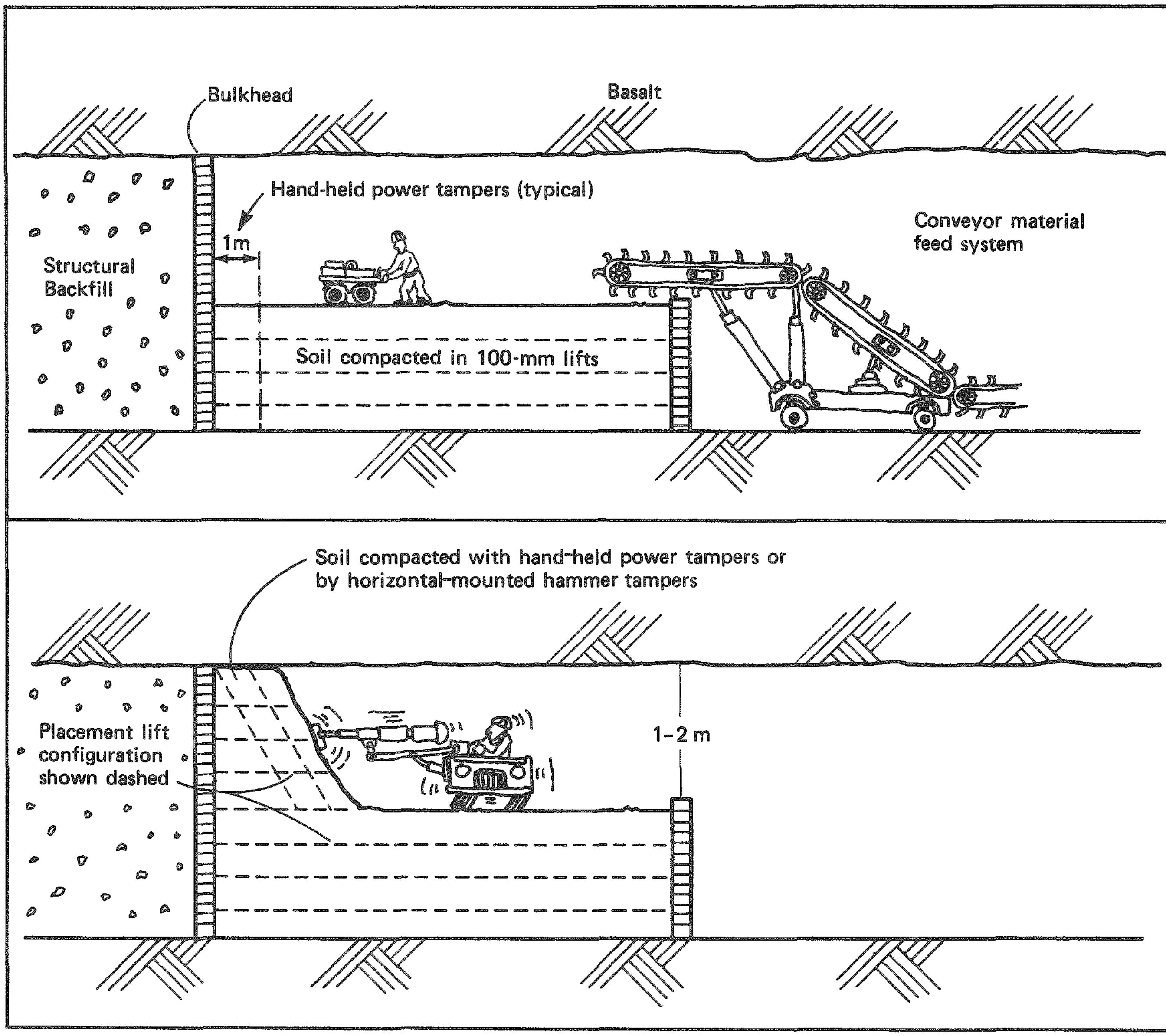


FIGURE 20

SMALL TUNNEL

PLUG SYSTEM

Material	Equipment
Basalt block or precomposed bentonite blocks with cement or bentonite mortared joints	Hand work Material feed system

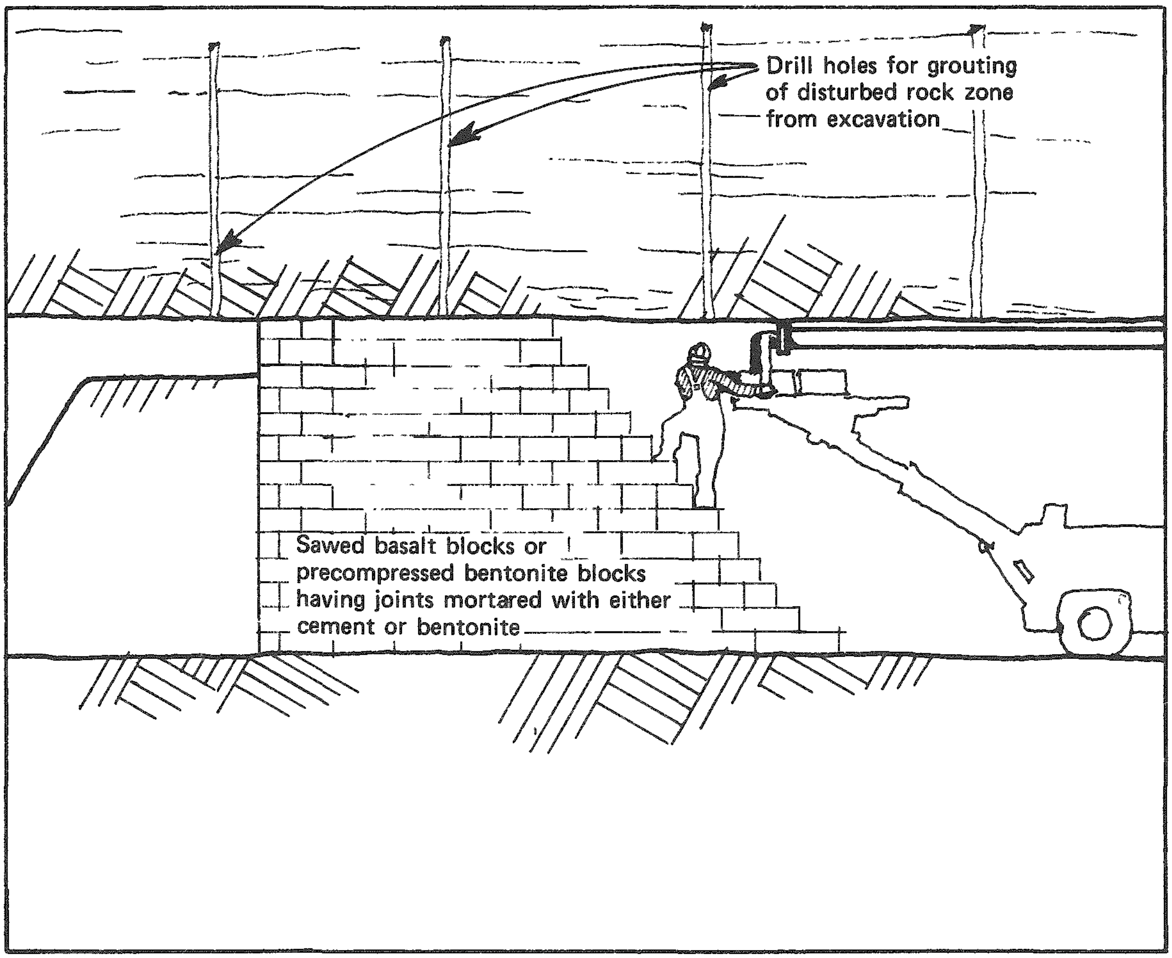
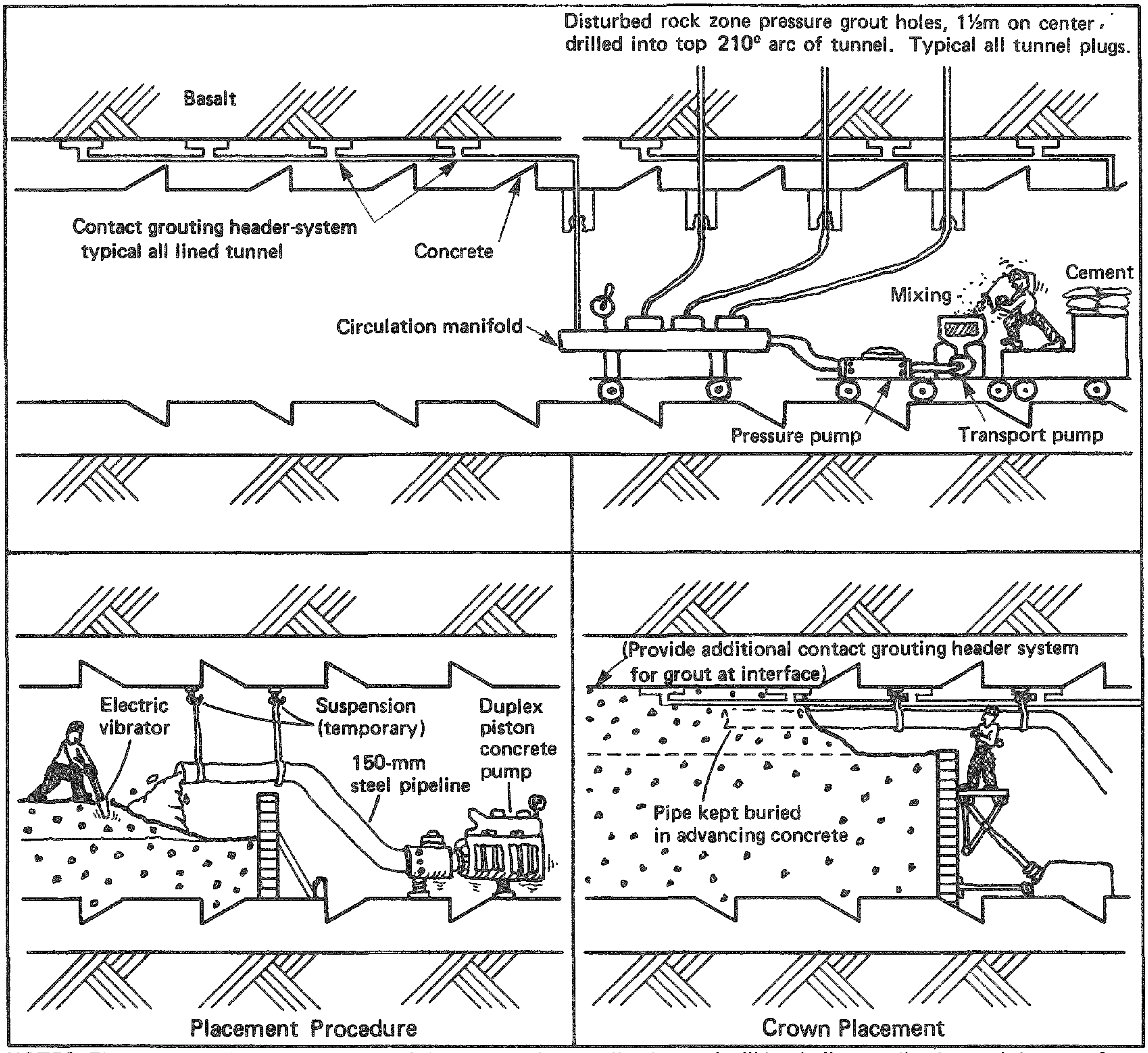


FIGURE 21

MASONED BLOCK PLUGS FOR TUNNELS

PLUG SYSTEM

Materials	Equipment
Concrete with 10-mm or 75-mm aggregate Clay slurry with 10-mm aggregate	Concrete pump system
Cement slurry Clay slurry	Grout pump system



NOTES: The procedure for the placement of the concrete in an unlined tunnel will be similar to a lined tunnel. In case of soil plug (e.g.,clay slurry with 10-mm aggregate), no liner is left in tunnel wall rock. Pressure grouting of disturbed wall rock in this case may be with a clay grout and contact grouting will be with a clay slurry.

FIGURE 22

LARGE TUNNEL

PLUG SYSTEM

Materials	Equipment
Clay/sand mixture with or without aggregate	Large earth rollers, supplemented with small compactors and tampers

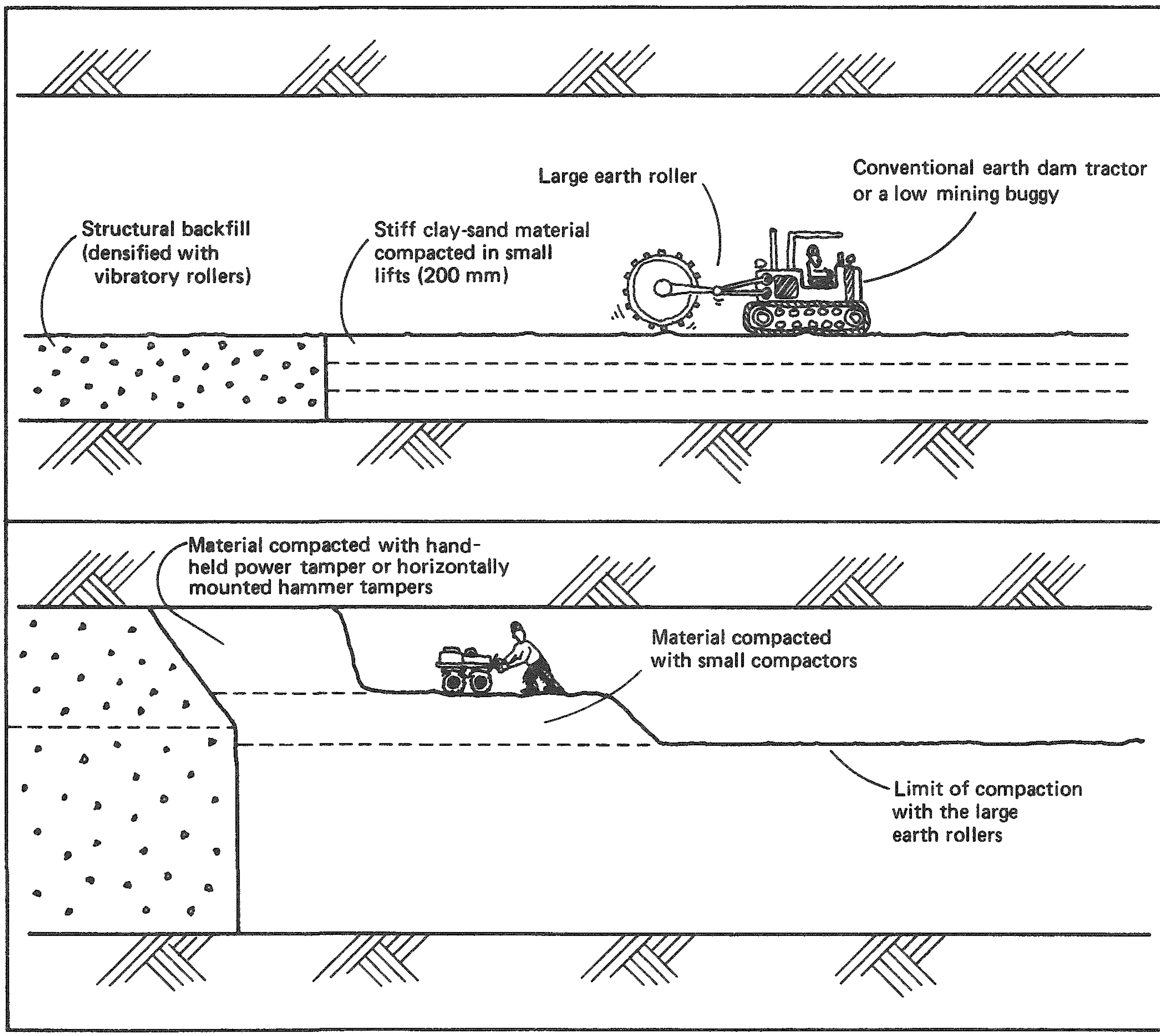
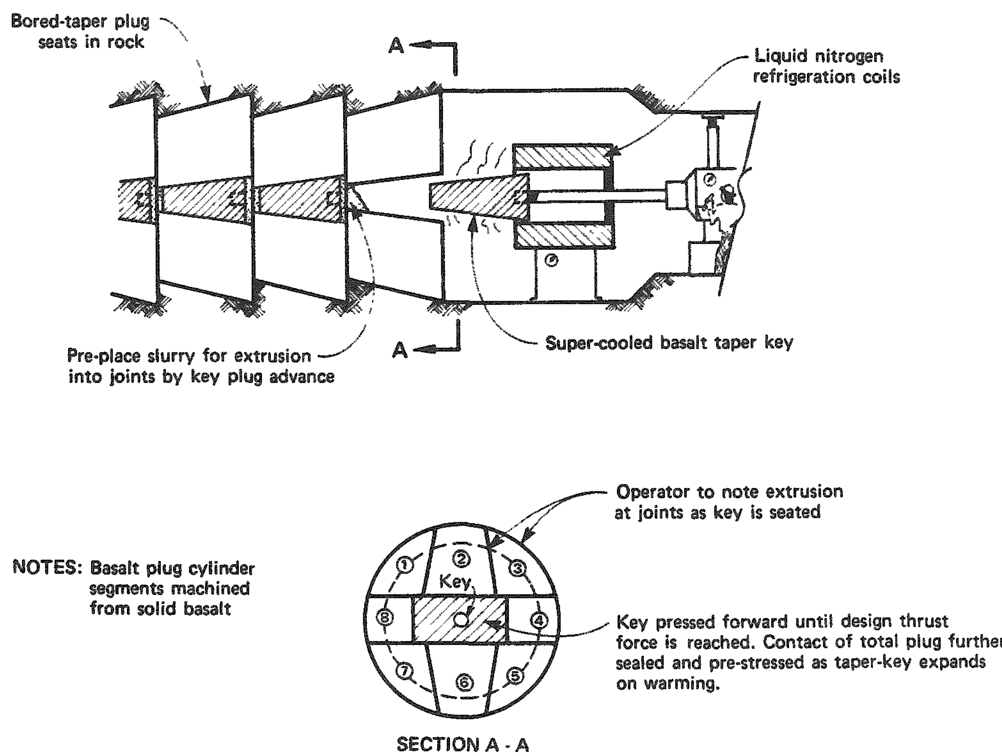


FIGURE 23

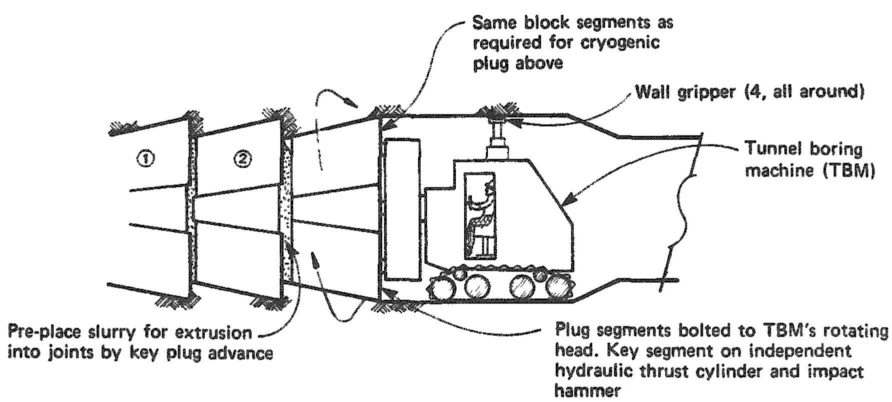
LARGE TUNNEL WITH A LONG PLUG

PLUG SYSTEM

Material	Equipment
Solid inclusion of basalt	As shown - R & D concept



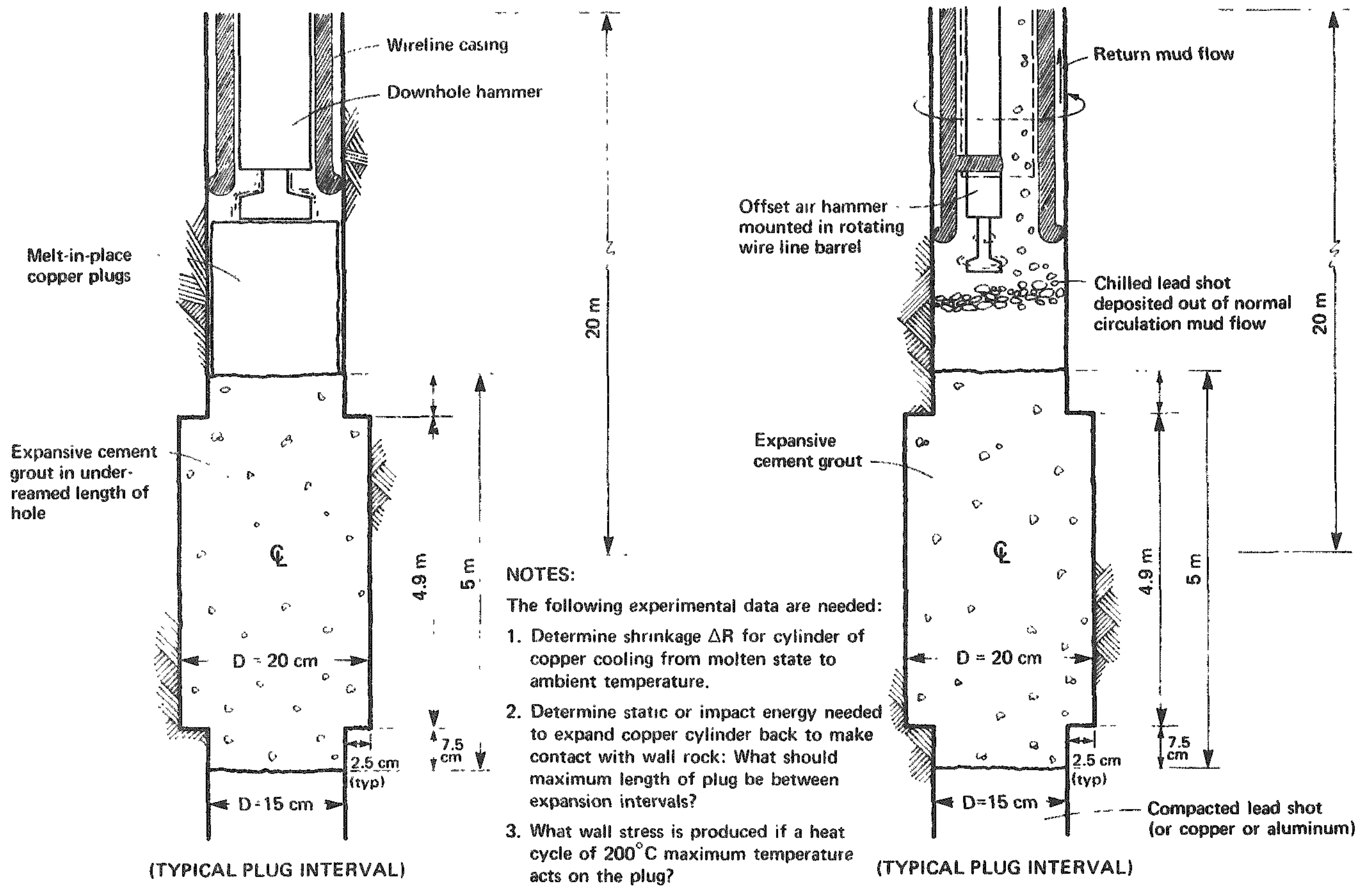
(a) CRYOGENIC PLUG



(b) TBM PLUG

FIGURE 24

SOLID BASALT ROCK PLUGS FOR TUNNELS AND SHAFTS

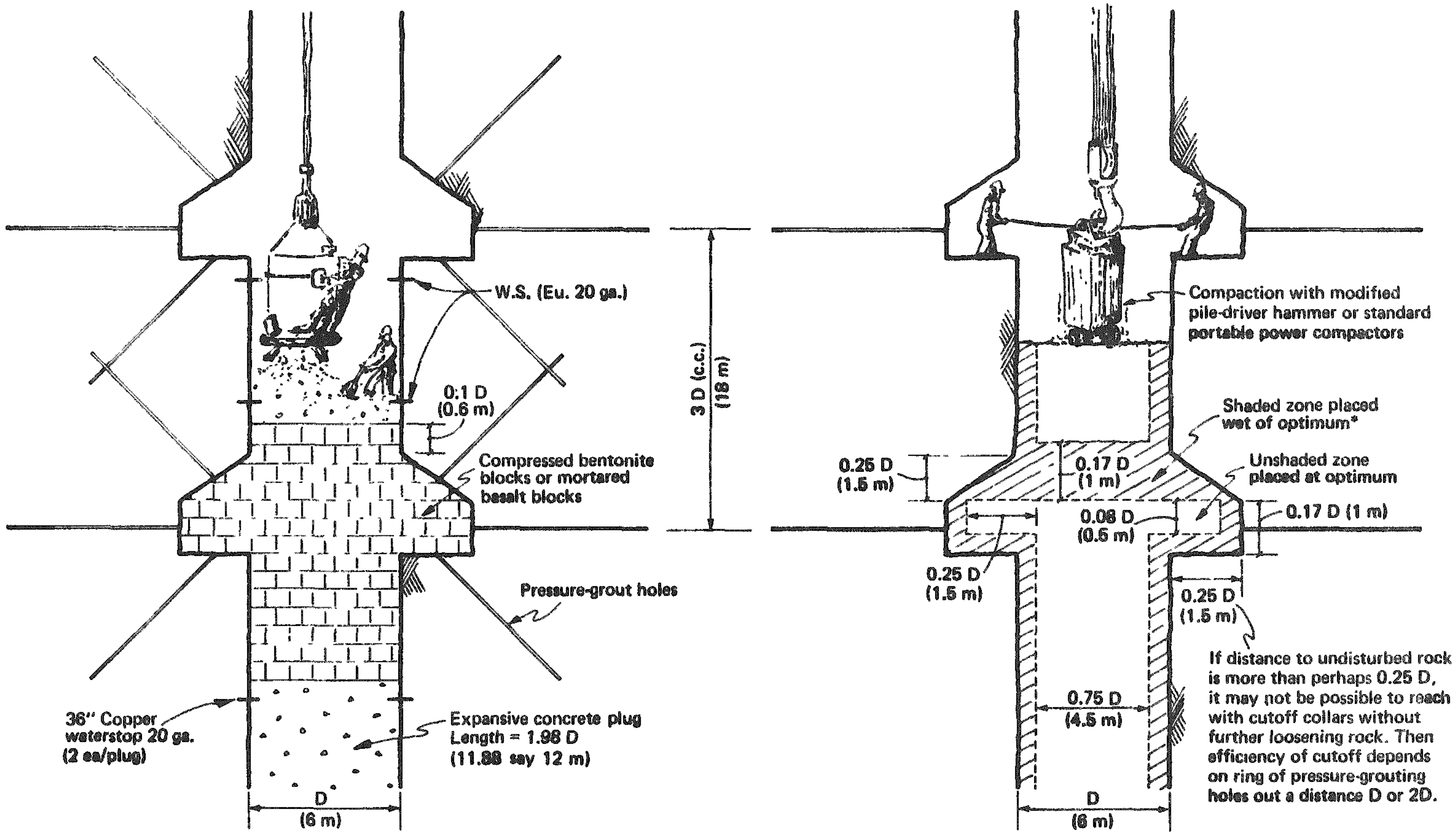


(TYPICAL PLUG INTERVAL) (TYPICAL PLUG INTERVAL)

COPPER AND GROUT PLUG (BOREHOLES) METAL SHOT AND GROUT PLUG

FIGURE 25

MULTIPLE-ZONE METAL AND CEMENT GROUT PLUGS FOR BOREHOLES



(a)

Multiple - Zone Concrete and Bentonite or Basalt Block Plug

(b)

Sand—Clay Plug

*Soil compacted at a moisture content in excess of that required to get maximum dry density at a given effort

FIGURE 26

MULTIPLE-ZONE CONCRETE AND BLOCK, AND ZONED EARTH PLUGS FOR SHAFTS

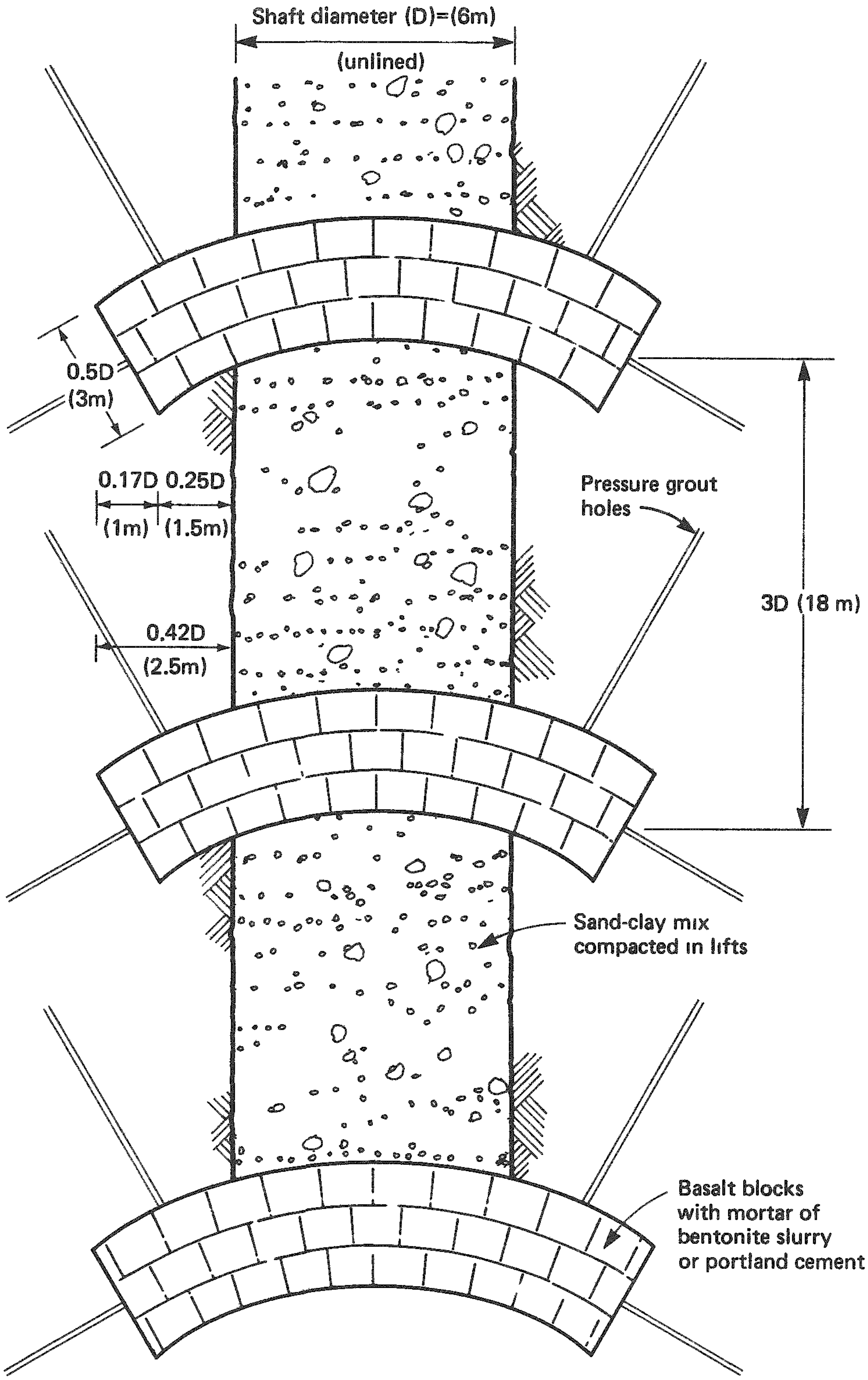


FIGURE 27

MULTIPLE-ZONE, MORTARED BLOCK ARCH AND CONCRETE PLUG FOR SHAFTS

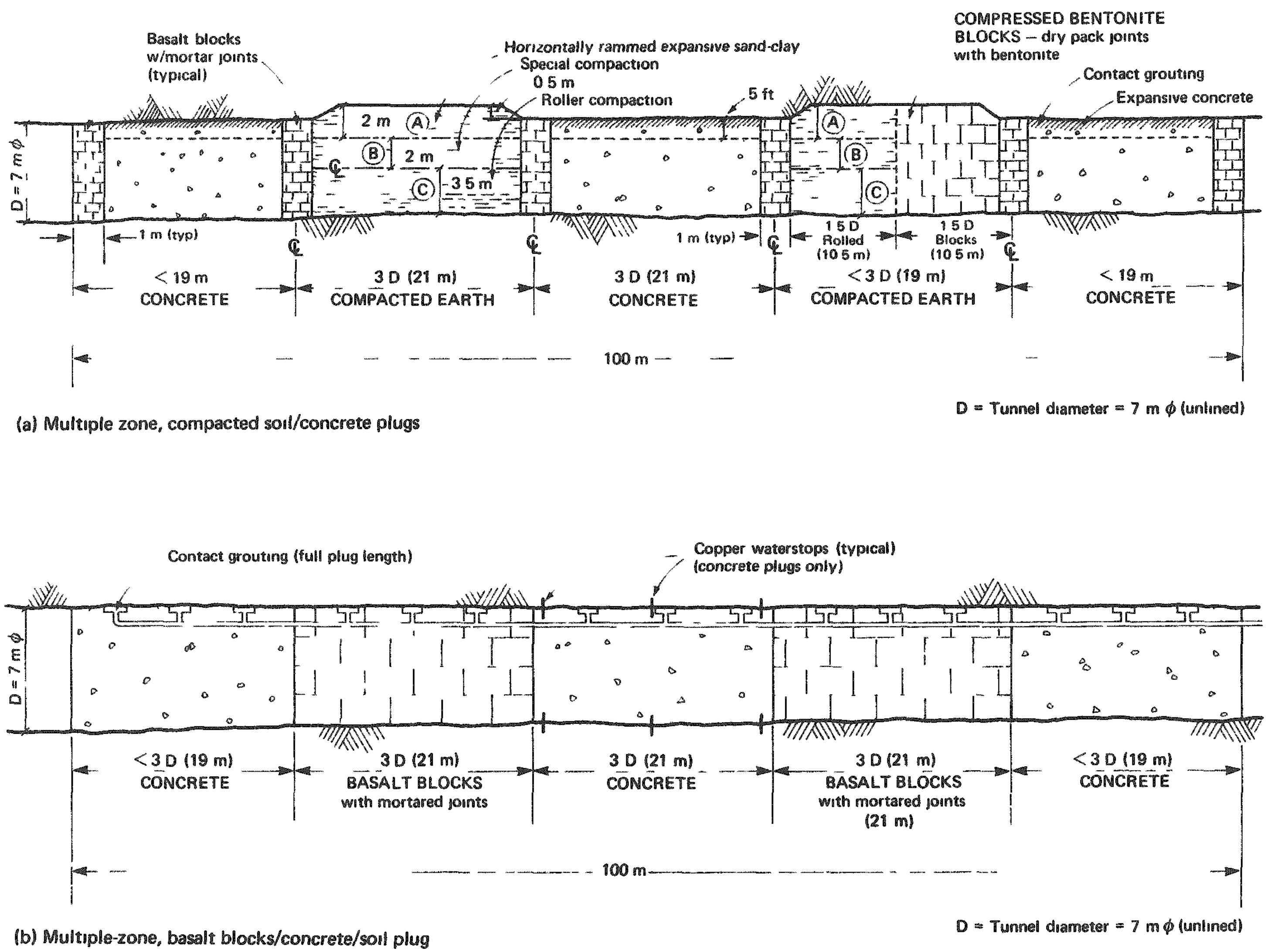
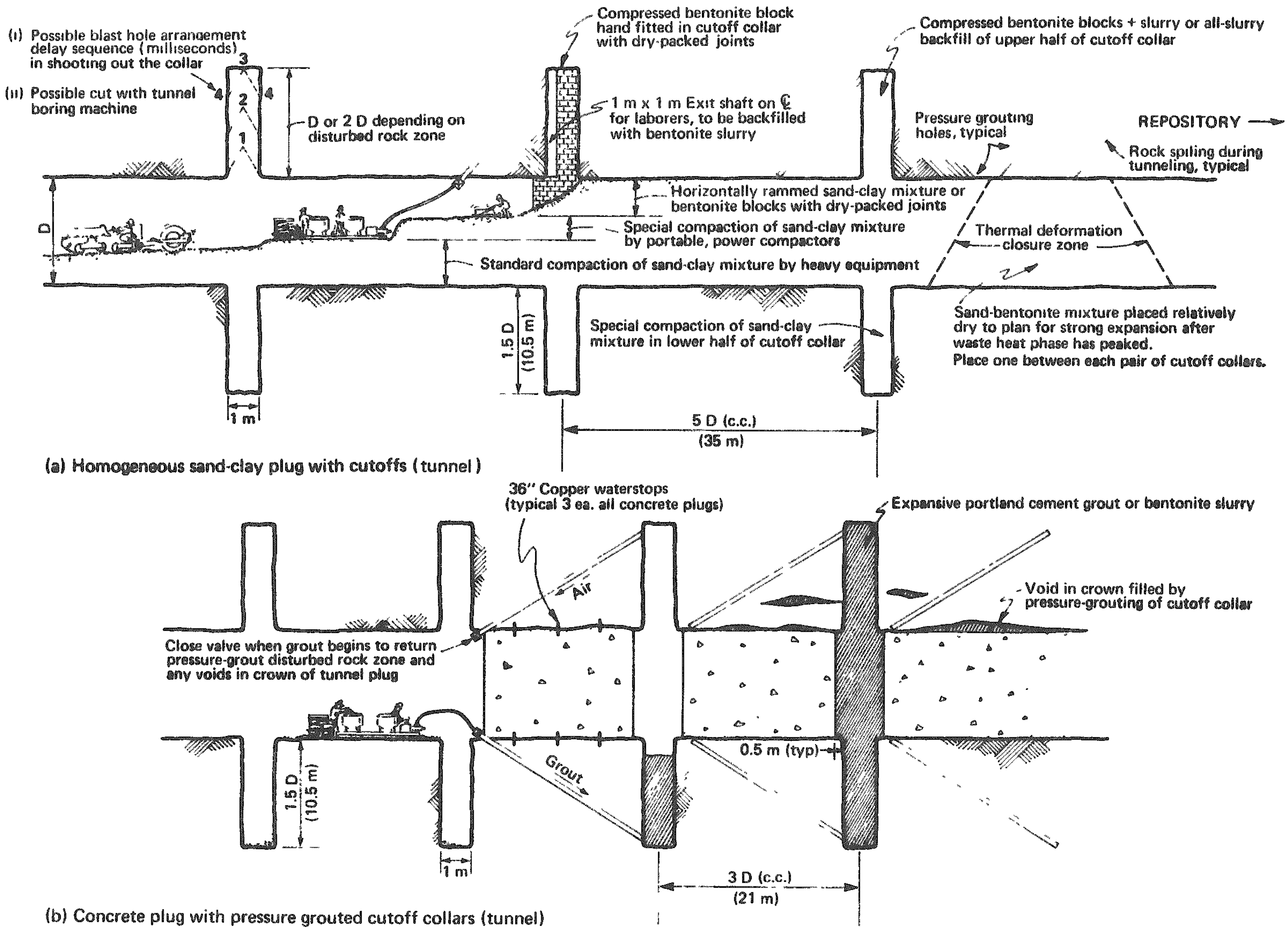


FIGURE 28
MULTIPLE-ZONE PLUGS FOR TUNNELS



(a) Homogeneous sand-clay plug with cutoffs (tunnel)

(b) Concrete plug with pressure grouted cutoff collars (tunnel)

FIGURE 29

MULTIPLE ZONE PLUGS WITH CUTOFFS FOR TUNNELS

(2) Shafts (Figures 16 to 18 and Figure 24)

Material	Placement System
(a) 75-mm or 10-mm aggregate concrete	Wireline/vibration
(b) 75-mm or 10-mm aggregate concrete	Concrete pump/ vibration
(c) Clay slurry	Grout pump
(d) Cement slurry	Grout pump
(e) Stiff clay (with or without 10-mm aggregate)	Wireline/small compactors
(f) Pelleted bentonite and aggregate	Wireline/small compactors

(3) Borehole Originating Underground

(3a) With the plug at a distance from a larger working area (Figures 8 to 15)

Material	Placement System
(a) 10-mm aggregate in a clay slurry	Concrete pump
(b) 10-mm aggregate in a cement slurry	Concrete pump
(c) Cement slurry	Grout pump
(d) Clay slurry	Grout pump

(3b) With the plug near a larger working area (Figures 8 to 15 and Figure 19)

Material	Placement System
(a) As for (3a) (a - d)	-----
(b) Stiff clay (with or without 10-mm aggregate)	Small compactor mounted on a jumbo
(c) Pelleted bentonite and aggregate	Small compactor mounted on a jumbo

(4) Tunnels (Figures 20 to 22 and Figure 24)

(4a) Small Tunnels

Materials	Placement System
(a) 75-mm or 10-mm aggregate concrete	Concrete pump vibration
(b) Clay slurry	Grout pump
(c) Cement slurry	Grout pump
(d) Stiff clay (with or without 10-mm aggregate)	Small compactors

(4b-i) Large tunnels with short plugs (Figures 20 to 22 and Figure 24)

Materials	Placement System
(a) Same as for (4a) (a - d)	-----

(4b-ii) Large tunnels with long plugs (Figures 21 to 24)

Materials	Placement System
(a) Same as for (4a) (a - d)	-----
(b) Stiff clay with aggregate up to 75 mm	Large rolling equipment

The preconceptual multiple-zone plug schemes (Figures 25 to 29) represent various combinations of the monolithic plug schemes illustrated in Figures 8 to 24.

2.3.2 Comments on Plug Schemes

The available schemes devised and discussed in this report must be recognized as being preconceptual and in need of analytical and field demonstration of their viability. Some of the schemes, such as the placing of concrete plugs in large-diameter lined tunnels, are conventional civil construction methods that are closely akin to the anticipated operation needed for waste isolation plugs. However, the materials and performance specifications for the latter are much more demanding and the environment is more difficult. Experience with earthmoving and compaction processes developed for engineered fills lends some level of confidence toward the viability of these schemes for waste isolation plugging; however, the technology transfer to the constricted space and difficult environment of basalt borehole plugging is an order of magnitude more uncertain than for concrete plugs.

Only a few of the problems faced by the preconceptual schemes in the various basalt borehole plugging environments are discussed in the following.

2.3.3 Borehole Originating at the Surface

For reasons discussed earlier, the available schemes for this plug environment are all of the pumped slurry type. It is anticipated that pressure grouting may be used to help reseal the disturbed basalt around the hole. Similarly, under-reamed cutoffs may be effective in sealing off the disturbed basalt.

If the plug is to be set at a position other than at the bottom of the hole, then a structural backfill could be placed in the hole up to the desired plug location. If this backfill is permeable, it may be necessary to place a sealing or filter layer above the backfill to prevent the plug material from moving into the backfill.

2.3.4 Shafts

One of the problems anticipated during shaft construction will be the protection of the workers during material feeding and compaction operations. Some sort of protective enclosure must be designed, such as that shown schematically in Figures 11 to 13. A more complex problem will be the sealing of the damaged basalt. Pressure grouting may only be a partial solution; grouting may not effectively treat fractures and loosened joints that have lower permeability than that represented by a hydraulic conductivity coefficient of about 10^{-5} or 10^{-6} cm/sec whereas 10^{-8} or 10^{-9} cm/sec may be needed for design goals.

The placement and compaction of either the slurry materials or the stiff clayey materials will be relatively straightforward. The slurry materials can be vibrated to produce a dense plugging material. Most of the compaction of the stiff materials can be done with small, self-propelled compactors. Compaction around the walls and into irregularities, such as cutoffs, will be done with hand-held power tampers. This is expected to be a difficult problem area.

2.3.5 Borehole Originating Underground

2.3.5.1 Plugs at a Distance from a Large Working Area

The plugging of holes below the horizontal can be accomplished in a fashion similar to the plugging of surface holes. The problems will probably be less difficult due to the shorter distance to the plug location, as compared to the surface holes. For holes above the horizontal, a slurry may be needed and a packer or valve would have to be used to prevent the slurry material from running out of the hole.

2.3.5.2 Plug Near a Large Working Area

These holes can be plugged with either a pumped slurry or a stiff clayey mix. A placement scheme for the pump slurry is as shown in Figure 9. A schematic of the placement technique for the stiff clayey mix is shown in Figure 19. Also shown are the methods for material delivery. The compaction should be carried out in small increments, the specific size of which should be confirmed by field tests on the actual plug material using the actual compaction device.

2.3.6 Tunnels

2.3.6.1 Bulkheads

It is anticipated that bulkheads will sometimes be used as permanent material supports during plug construction. It is possible that the bulkheads will be made of a degradable material, but this will not necessarily affect the performance of the plug. The bulkheads will all be constructed perpendicular to the flow through the plug so they will not provide a path for seepage through the plug. The bulkheads can be constructed of materials that react with the plug environment to produce geochemically stable reaction products, such as aluminum, which occupy a volume that is equal to (or greater than) that volume occupied by the original material. These reaction products will be prevented from moving by the plug and by the structural backfill on either side of the plug, and consequently, no large voids will be created by the alteration of bulkhead materials, precluding any loss of structural support.

3 ANALYSIS OF PRECONCEPTUAL PLUGGING SCHEMES

The numerous preconceptual plugging schemes identified in Section 2 were developed with a general knowledge of the problems that could arise during various stages of plug design, construction, and performance. Implicit in the development of these schemes was the assumption that, among the schemes, acceptable ones could be chosen for plugging boreholes, shafts, and tunnels. Acceptable plugs would be those that could be shown, by analysis, to satisfy the criteria of core barrier performance, plug-wall rock interface performance, support performance, disturbed zone performance, and long-term integrity. By incorporating various aspects of plug design, construction, and costs into these performance criteria, a comprehensive evaluation of the acceptability of the preconceptual plugging schemes has been made.

Three approaches were used in evaluating the relative acceptability of the plugging schemes. The first approach, technical analysis, incorporated numerical, probabilistic, and cost analyses, not only to evaluate the anticipated performance characteristics of the plugging schemes but also to confirm the validity of the assumption that an acceptable plug could be chosen at all. For the second approach, dominance analysis, rating matrices, and decision analysis techniques were used to rate the relative strengths and weaknesses of the plugging schemes. In the third approach, expert judgment, a questionnaire format was used to obtain the judgment of experienced evaluators relative to the feasibility and performance of the preconceptual plugging schemes. Finally, the results of these three analysis techniques were compared, major discrepancies were reconciled, and a consensus was reached as to the most acceptable plugging schemes.

3.1 TECHNICAL ANALYSIS

In the absence of specific design criteria, engineering judgment was used to define the many design parameters, making possible a technical analysis of the preconceptual plugging schemes, although one limited in scope. It was determined that the most productive analysis could be performed by developing several different models to evaluate what are considered the most important aspects of plug design, such as thermal stresses in the plug, sliding stability of the plug, and water flow out of the repository. For each model, parameters (such as plug diameter, hydraulic gradients along the plug, and plug rigidity) were assumed to be constant or varied over a limited range of values because these could be estimated with the greatest degree of confidence. Using these models, it was possible to evaluate the effect of parameters, such as plug permeability, plug shear strength, the zone of disturbed basalt around the plug, and plug retardation coefficient on design parameters (such as plug length and the use of cutoff collars extending into the zone of disturbed basalt). Although limited in scope, these models proved to be valuable for illustrating the plug design and construction parameters that will have the greatest impact on plug performance.

3.1.1 Definition of Problems for Analysis

For engineering analysis of the plug, two key questions must be resolved:

(1) Is the flow through the plug within an allowable range?

(2) Is the plug stable?

Because no performance data for comparable plugs are available, a modeling program was undertaken to provide approximate answers to these questions. This section discusses the scope of the modeling program, including an assessment of the "worst case" plug conditions that may need to be studied. Initial judgmental data for the modeling include:

- Design criteria;
- Construction techniques (including dewatering);
- Repository heat load;
- Plug geometry; and
- Geological conditions (in-situ stress and hydrology).

The judgmental data adopted herein are presented in Appendix A.

3.1.1.1 Design Criteria

For plug design, specific design criteria are useful to help identify the best plug configurations prior to the evaluation of the repository as a whole. It has been proposed that the plug be designated as Class I, II, and III,* defined roughly as follows:

- Class I: Primary barrier to flow of contaminated ground water out of the repository; plug

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* These definitions are conceptualized after NRC definitions for licensing nuclear reactors. In Regulatory Guide 1.29, Seismic Category I structures are defined as those which should be designed to withstand a Safe Shutdown Earthquake (SSE) and remain functional.

should be able to withstand the maximum design load* and remain functional.

- Class II: Same capabilities as a Class I plug, but farther from the repository or back-up plug.
- Class III: Generally capable of reducing flow through boreholes and providing structural support.

These definitions are not sufficiently specific for engineering design. To facilitate design, several design criteria have been identified for the preconceptual studies. These criteria are not necessarily recommended design limits; they are useful for selecting preferred candidate plugging schemes.

<u>Design Criteria for Flow</u>

The three possible design criteria for flow that can be used in the design process are:

(i) <u>Allowable seepage</u> through the plug, plug-basalt interface, and damaged wall rock. This approach would specify a maximum annual seepage rate. Note that any instability of the plug that causes cracking or failure will increase seepage. Thus, this criterion implies a condition of plug stability. A possible allowable seepage might be 1 m^3/year for 10,000 years.

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* The maximum design load is the combination of probable worst-case thermal, hydraulic, and mechanical loads that produce the lowest factor of safety against failure.

(ii) Seepage travel time through the plug, plug-basalt interface, and damaged wall rock. This approach would specify how long it must take for one drop of water to traverse the plug. A travel time of 10,000 years has been suggested. This is a more restrictive criterion than (i) above.

(iii) Equivalent undisturbed basalt flow resistance. The plug should be able to resist flow at least as well as the intact rock. The length of the plug may be limited by the distance of the repository from the biosphere. That distance might be defined as the distance from the repository to the nearest potential aquifer resource above the repository. The distance to the biosphere could also be taken as the distance to the ground surface. In either case, the relationship between plug permeability and plug length may be stated as follows:

(a) For vertical shafts and boreholes, the plug must have an equivalent or better hydraulic resistance than the material excavated from the biosphere horizon of the shaft (or borehole) to its base. This means that:

$$\frac{k_p}{L_p} = \frac{1}{\sum_{i=1}^{n} \frac{L_i}{k_i}} \quad (3.1)$$

where:

- k_p is the permeability of the plug;
- L_p is the length of the plug;
- k_i is the permeability of the i^{th} layer through which the shaft passes; and
- L_i is the thickness of the ith layer through which the shaft passes.

(b) For horizontal boreholes and tunnels, the plug must have an equivalent or better hydraulic resistance than the material excavated over the length of the tunnel or borehole. This means that:

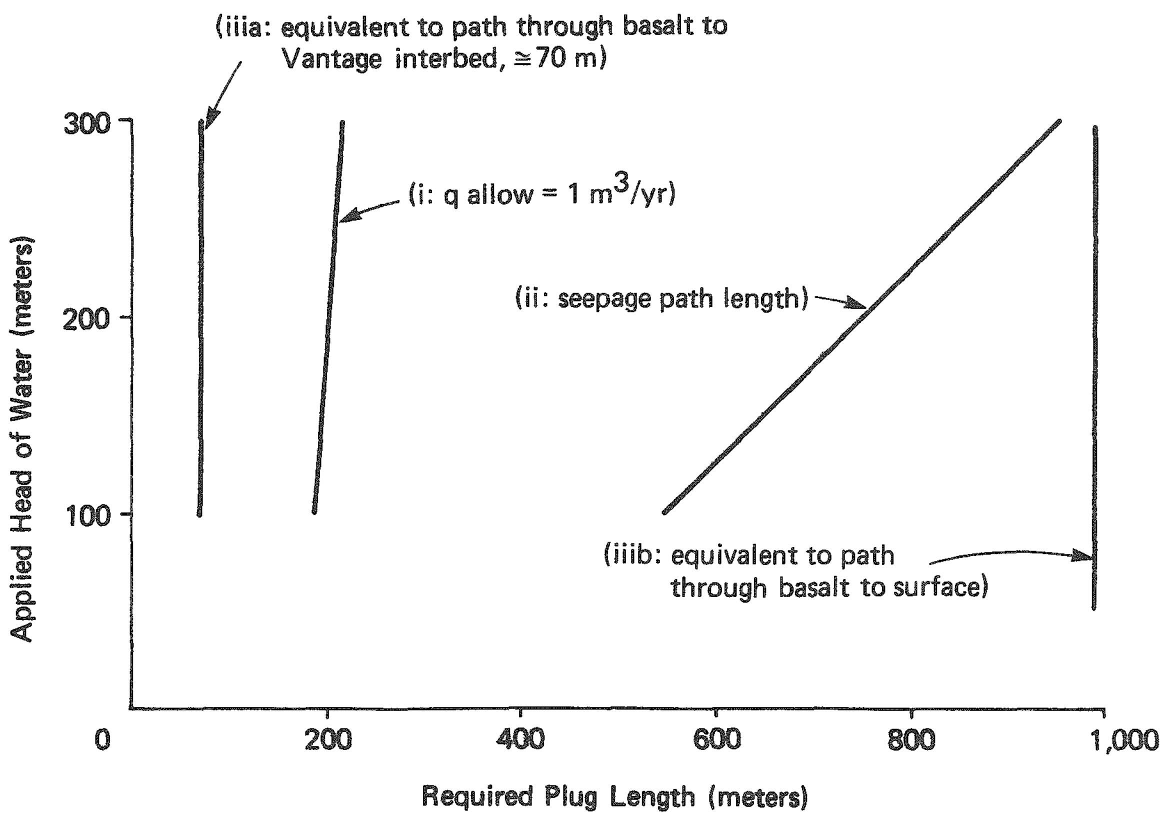
$$\frac{k_p}{L_p} = \frac{k_B}{L_B} \qquad (3.2)$$

where:

- k_B is the permeability of the basalt layer in which the tunnel is located; and
- L_B is the total length of the tunnel.

(iv) Allowable radioactive contaminant escape. This criterion would specify the amount of radioactive material that could allowably pass through the plug over a period of one year. The design would include the ability of certain potential plug materials to retard radioactive materials. Data on sorptive properties are not well defined for candidate plug materials at this time and this makes it difficult to use this criterion. Implications of preconceptual design to this criterion are deferred to Section 3.1.4.

Figure 30 compares the three criteria (i), (ii), and (iii) for a simple case. For the present case, we will use (i), which is



NOTES:
(1) (i), (ii) and (iii) refer to seepage criteria discussed in text.
(2) Material for plug assumed to have $k = 10^{-8}$ cm/sec and $n_{eff} = 1\%$, where n_{eff} = effective porosity.
(3) Assume saturated, steady state flow.
(4) Repository at 1,000-m depth; all strata have $k = 10^{-8}$ cm/sec.

FIGURE 30

REQUIRED PLUG LENGTHS FOR SEVERAL SEEPAGE CRITERIA easier to define than (iii). Criteria (ii) and (iii) may prove to be excessively conservative because neither criterion considers the sorptive capabilities of the plug and (ii) does not consider distance to the biosphere.

Design Criteria for Plug and Plug Environment Stability

The plug may meet the previous flow design criteria and have only a factor of safety of 1 for stability. Because of the variation in soil or rock parameters in any mass and because of our inexact knowledge of the geology, hydrology, and other parameters, it is necessary to use a higher factor of safety.

Rockwell (1980) recommended a factor of safety of 2 on stress in basalt for repository operation conditions and room scale design. For mass retrievability conditions and room scale design,* a factor of safety of 1.25 was recommended and for room scale and long-term analysis a factor of safety of 1 was recommended. A factor of safety of 2 was recommended for long-term analysis of joint slip. A factor of safety of 1.5 on basalt strength was recommended for entries and shafts during repository construction and operation, up to the time of plugging, and a factor of safety of 1.0 was recommended for long-term analysis of these features.

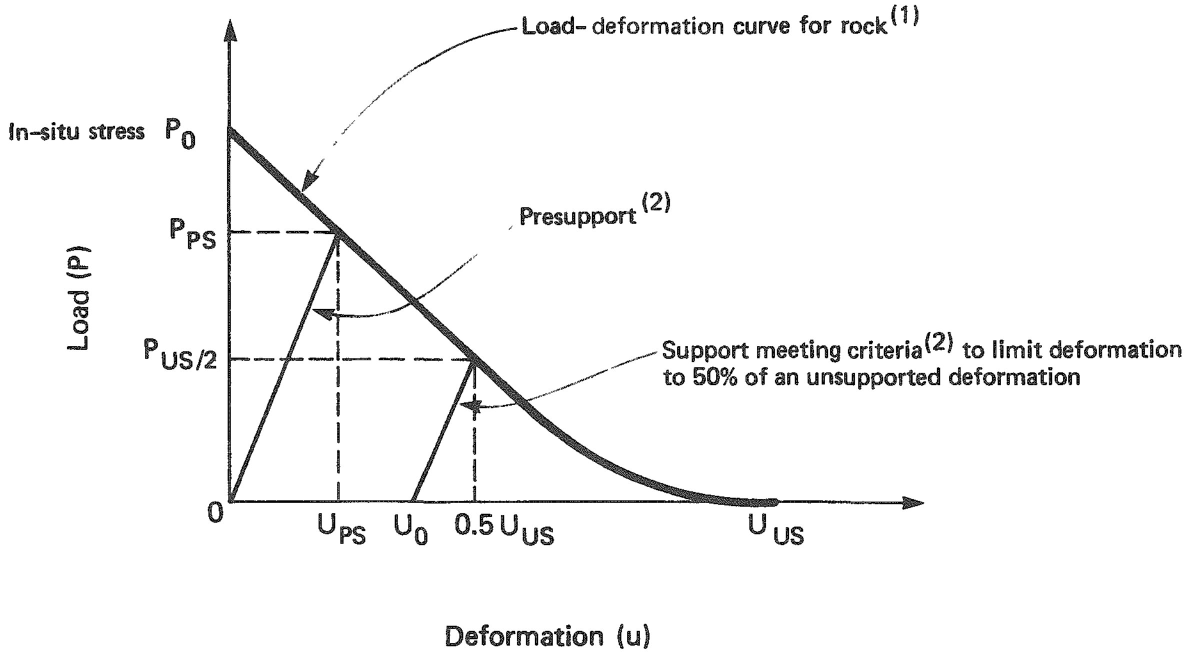
The factors of safety recommended for those general features were considered with respect to their contiguous relationship with plug locations and accordingly the following will be used for plug modeling:

* Must excavate backfilled repository to retrieve canisters. Access tunnel and shafts still open.

Material	Factor of Safety At Time of Plugging	Long-Term Factor of Safety
Basalt	1.5	1.0
Basalt joints	2.0	2.0
All plug components	2.0	1.5

The factor of safety is defined as strength/stress. The strength is defined as the available strength of a rock mass subjected to a design stress condition, generally including an in-situ rock stress and an induced stress change caused by construction activities. In order to assess the available strength of an in-situ mass of basalt, typically characterized by discontinuities (such as joints and fractures), the dimensions of the affected rock mass must be determined so as to allow for the effects of the included discontinuities. For rock mechanics analyses of excavation performance, the available strength will be based on a cube of rock mass that has side dimensions equal to 1/6 the span dimension of the cavity, at a distance from the cavity side equal to 1/12 the span dimension (Rockwell, 1980). For boreholes, the side dimensions of the representative rock mass are 1/6 the borehole diameter. Although these criteria suggest allowable stress levels on the basis of available strength, the stress levels may have to be compared to the upper limit of elastic stress/strain performance of the rock. If the stress level is in the inelastic range, then any stress decreases during the plug history, such as during thermal unloading, may cause an unacceptable increase in permeability.

Figure 31 shows a characteristic curve of rock pressures that might be exerted by the wall rock of an excavation on a construction support system. The more flexible the support



NOTES: (1) The load-deformation curve is shown for a tunnel in good rock which may stand unsupported. At equilibrium, the unsupported rock ($P = 0$) will have displaced by the amount $u = u_{us}$.

(2) Presupports are placed before any deformation occurs (at $u = 0$). Due to the presupports' finite stiffness, some displacement ($u = u_{ps}$) occurs after support placement.

(3) A support meeting criteria for 50% of the unsupported deformation is shown. It is placed a few feet behind the face, with some deformation ($u = u_o$) having already occurred. The final displacements, including elastic compression of the supports, are $u = 0.5u_{us}$. (Note: This is an example only only and not a recommendation for allowable deformation.)

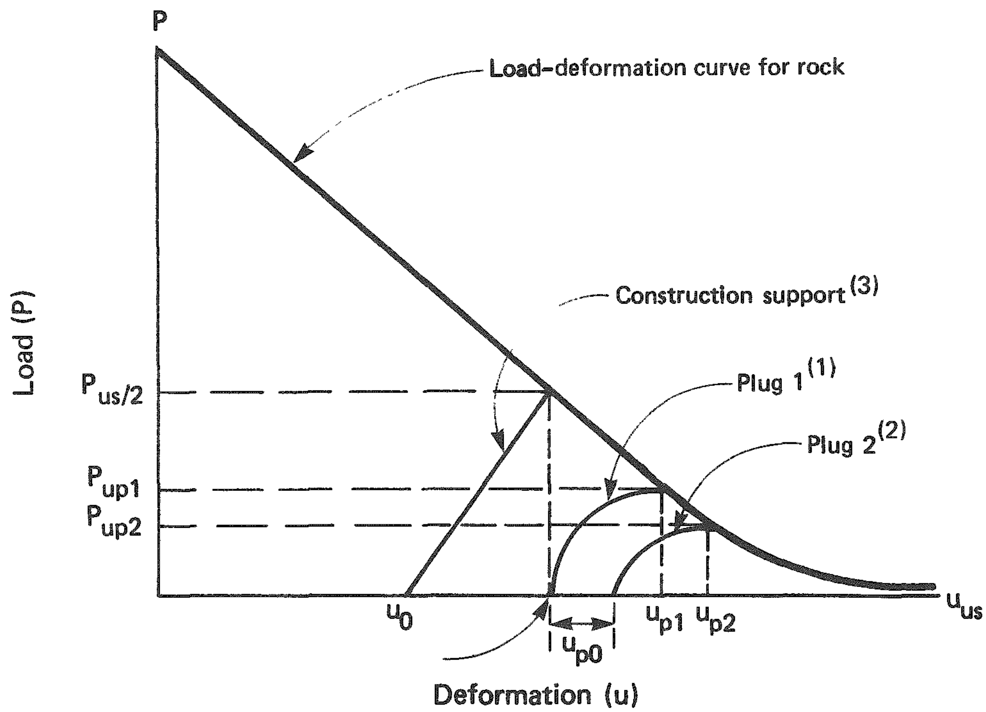
After Schwartz and Einstein (1978)

FIGURE 31

RELATION BETWEEN SUPPORT TYPES AND POSSIBLE DEFORMATION CRITERIA system is, the more deformation of wall rock into the excavated opening. During the deformation process, the wall rock assumes an increasingly larger proportion of the loads needed to balance the lithostatic pressures acting on the excavated opening (e.g., mobilizes more of its available strength), and the support system assumes less of the loads. To safely reach a range of minimum required support pressure in the theoretical example shown in Figure 31, a suitable component rock and careful excavation methods (conditions expected to be potentially available in the repository construction) would be required. Nonetheless, the need to control permeability by controlling wall rock deformation may necessitate placing construction supports to arrest the deformation of the wall rock as shown in an example on Figure 31. Some deformation will occur even with pre-support (for example, spiling bolts placed ahead of the excavation face, which may not be practical or allowable for this project). Plug placement may then cause additional loosening if the initial suport system is removed before plugging, as shown in Figure 32. Field tests are needed to investigate the relationship of convergence vs. wall rock permeability changes to establish support design criteria. Furthermore, this functional relationship should be verified by performance instrumentation monitoring during actual cavity excavation and support.

3.1.1.2 Effect of Construction and Support Methods

Some wall rock will be disturbed and destressed as a result of the excavation. Two processes will affect the extent of disturbance and may cause loosening of rock blocks and radial inward movement of the disturbed zone. They are: (1) stress relief; and (2) loosening and overbreak caused by energy transfer into the rock by the construction process (such as



NOTES:
(1) Plug 1 is a granular material, placed at the same time the support is removed.
(2) Plug 2 is a granular material, placed in steps as small portions of supports are removed. Thus, some displacement ($u = u_{p0}$) occurs prior to plug placement.
(3) Plugs are shown as less stiff than the construction supports and with non-linear properties. Rock deformation will increase (as a result of plug placement) to u_{p1} or u_{p2}.

After Schwartz and Einstein (1978)

FIGURE 32

EFFECT OF PLUG PLACEMENT ON BASALT DEFORMATION blasting). The presence of the disturbed zone may have important implications for plug design. First, if loosening occurs, permeability may increase in the disturbed zone. Also, loosening may decrease the wall rock stiffness and strength. The resulting material properties are expected to influence plug placement techniques and potential stress concentration locations over the life of the repository.

Effect of Permeability

Due to the decrease in confining pressure normal to the tunnel, shaft, or borehole wall, permeability may increase in the zone of stress relief. In Figure 33, the zones of interest are outlined for three stress conditions. Tangential boundary stresses may also be locally decreased, particularly where the horizontal and vertical in-situ stresses are different, and potentially increase permeability to flow in the direction perpendicular to the tunnel, shaft, or borehole axis.*

Permeability of sandstones has been shown to increase by a factor of 2 (Wyble, 1958) when the confining pressure decreases from 35 MPa to 0 MPa. Similar results were found by Nelson (1976) for fractured sandstone. In basalt, the same level of increase in permeability for a single fracture was found by Iwai (1976) for a confining pressure decrease from 20 to 5 MPa; however, permeability increased by 10^2 between 5 and 0 MPa.

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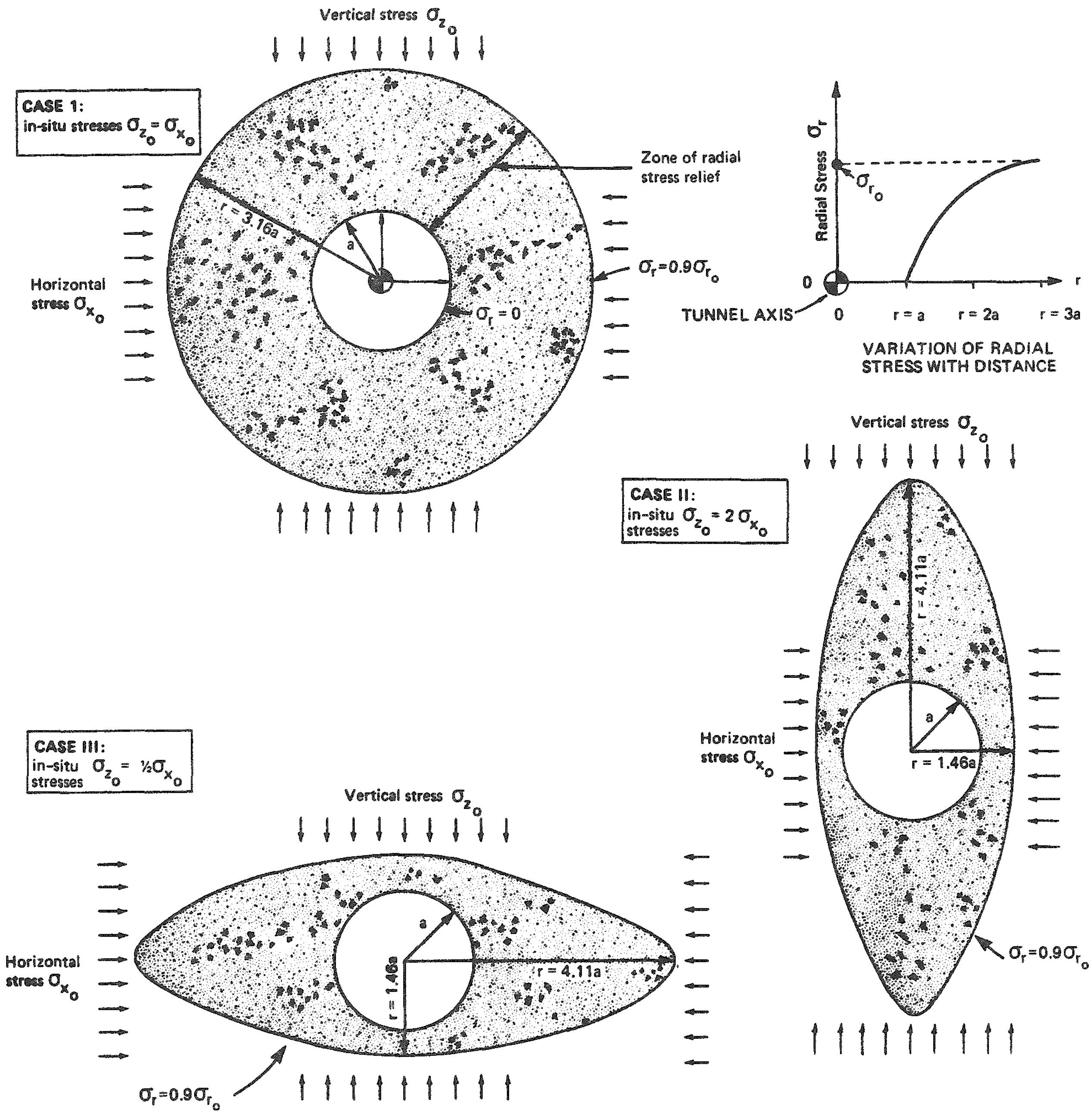
* Tangential boundary stresses may also locally reach high compressive values that have important implications for stability.



NOTES: Direction of increased permeability is parallel to axis of plug. This may lead to increased flow around the plug and bypassing it.

Stresses perpendicular to tunnel axis:

σ_x = horizontal stress
σ_z = vertical stress
σ_r = radial stress

FIGURE 33

ZONE OF ELASTIC STRESS RELIEF

In addition to stress relief, mechanical energy transferred into the rock by the excavation process (e.g., blasting) may loosen the rock and open or create new fractures. Any source of increase in fracture aperture, e, will increase the fractured rock permeability, k_f. The relation between those two factors is of the form $k_f = e_3$ (Goodman, 1976), so that the combined effects of stress relief and mechanical loosening may have a potentially significant impact on basalt permeability. This impact must be considered in plug analysis.

Excavation Techniques that Minimize Loosening

As noted above, there are two sources of loosening in tunnel and shaft construction. One is deformation due to stress relief prior to and during suppport placement (see Figure 31). The second source is mechanical loosening caused by energy transferred into the rock by the excavation process. Careful excavation and construction techniques can minimize both sources of loosening.

Presupport by pre-grouting or by the use of spiling reinforcement can be an effective way to limit stress relief deformations (see Figure 31). Placing supports as close to the face as possible can also reduce deformation, but some deformation will occur before support placement as the stress is reduced due to an approaching face. Mechanical loosening can be controlled by careful excavation. For example, for drill and blast operations, short lengths of advance, reduced charges in perimeter holes, controlled deviation of blast hole drilling, and possibly prenotched drillholes will all help maintain the integrity of the rock. Careful monitoring during excavation at intervals along the excavation length may be necessary to demonstrate adequate control for a minimum disturbed rock zone around the excavation.

Once the construction techniques are identified, the modeling program would benefit from (1) existing or pilot scale field data on the use of those methods in basalt; and (2) good engineering-geology-type descriptions of the basalt (Rock Quality Designation [RQD], strike and dip of joint sets, roughness of fractures). With this information, it may be possible to estimate the extent and degree of loosening for site-specific cases.

Potential Plugging Problems Due to Repository Construction and Support

A discussion of some of the problems resulting from the presence of the disturbed zone may clarify why an understanding of this zone is important. If the disturbed zone is not treated prior to plugging, the effectiveness of the plugging scheme to retard flow will be diminished by flow bypassing the plug. In shafts or vertical boreholes (where only a limited vertical distance is between an overhead aquifer and the repository), this material could provide a "relatively high" permeability flow path between the repository and nearby aquifers. Remedial measures, such as grouting, may not be effective in reducing the permeability of the disturbed zone beyond perhaps 10^{-6} to 10^{-7} cm/sec. (Intact mass basalt has a reported permeability of 10^{-9} cm/sec.) Rock joint openings with permeabilities of $\sim 10^{-6}$ to 10^{-7} cm/sec are likely to be less than 50 microns (WCC, 1977). Grouting may be possible with a fine clay or chemical grout, but cement grout particles are too large to penetrate such small openings.*

Dependence on Dewatering and Rewatering Schemes

The plug design will also be dependent on the dewatering/rewatering schemes and the water-control measures used while the repository is in operation. It is assumed that some form of dewatering will be used during the construction of the repository and during the retrievability period of repository operation. This dewatering may simply involve removal of water that drains into the repository tunnels and shafts, or it may be a more active approach, such as the use of wells. In some cases, the use of tunnel and shaft liners that have weepholes is adopted to prevent build-up of high hydrostatic loads on the liners. In other cases, liners are designed to resist any hydrostatic loading. The selection of a liner may affect how much weathering and erosion of joint infilling may occur. It may also affect the selection of plug placement techniques (discussed earlier in this report). For plug design, the following information about the dewatering plan would be useful: (1) details of dewatering techniques; (2) drainage control measures; and (3) effect of flow into repository on basalt weathering and weathering of joint fillings.

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* Based on grout particle sizes (as documented in Lenzini and Bruss, 1975). Note that soils of permeability 10^{-6} to 10^{-8} have flow channels of much smaller cross-sectional area than rock joints having the same permeability. Thus, $K = 10^{-5}$ cm/sec is usually the minimum permeability for a groutable soil.

Perhaps more important than dewatering, data are needed on rewatering. For plug design, it would be useful to know: (1) whether rewatering will be by natural means or be artificially accelerated; (2) how long the repository will be kept dry before rewatering; and (3) how long the rewatering process will take. Such rewatering would depend, in part, on the porosity of the repository after backfilling. This information may help the modeling program assess plug performance. The following examples show why these data can be important:

- Plug drying: If the plug dries out prior to rewatering, it may develop shrinkage cracks, which have high permeability after rewatering. Drying of joint infilling in the host rock around the plug might also increase the permeability of the wall rock.

- Maximum hydraulic load: If the repository is kept dry and leakage from overlying aquifers fills intercepting shafts or boreholes, then a very high differential head may be imposed on the plug.

- Steam: Thermodynamic considerations (P_{sat} at t = 200°C) suggest that a steam phase will be present in the repository until the water pressure reaches 1.6 MPa (about 160 m of water head). Due to the heating, both steam and water will tend to flow out of the repository under this pressure. Steam has a lower viscosity than water and thus may flow more easily through the plug. Velocity of steam may be of importance in various backfill materials from the standpoint of channeling or piping of fine soil. The volume of steam flow and the thermal stresses caused by the hot fluid heating a colder plug must be assessed.

In view of the unknowns and for the purposes of design, the following assumptions are made:

- Dewatering will only require the removal of water that drains into repository, tunnels, shafts, etc; and

- Natural rewatering will take 10 years to fill the estimated voids in a repository backfill (tunnels and shafts backfilled with clay/sand plugs may take up to 1,000 years to saturate, as will be shown later).

In addition to these procedural assumptions, an estimate is needed of short- and long-term hydraulic gradients or loads on the plug system. The following assumptions are made:

- A maximum head of 1,000 m acting toward the repository due to a shaft filling with water before the opening can be backfilled and while the repository is dry at the other end of a connecting, plugged tunnel;

- A maximum head of 160 m acting from the repository due to heating of the fluid filling the repository (the 160 m are equivalent to a water pressure of 1.6 MPa at 200°C); and

- A long-term horizontal gradient of 10^{-3} and a long-term vertical gradient of 10^{-2}, upward (based on a few, limited hydrogeologic data).

3.1.1.3 Dependence on Repository Heat Generation

The rate of heating of the plugs and the maximum temperature reached will depend on the heat generated by the waste in the repository. The heat load is important because it may cause:

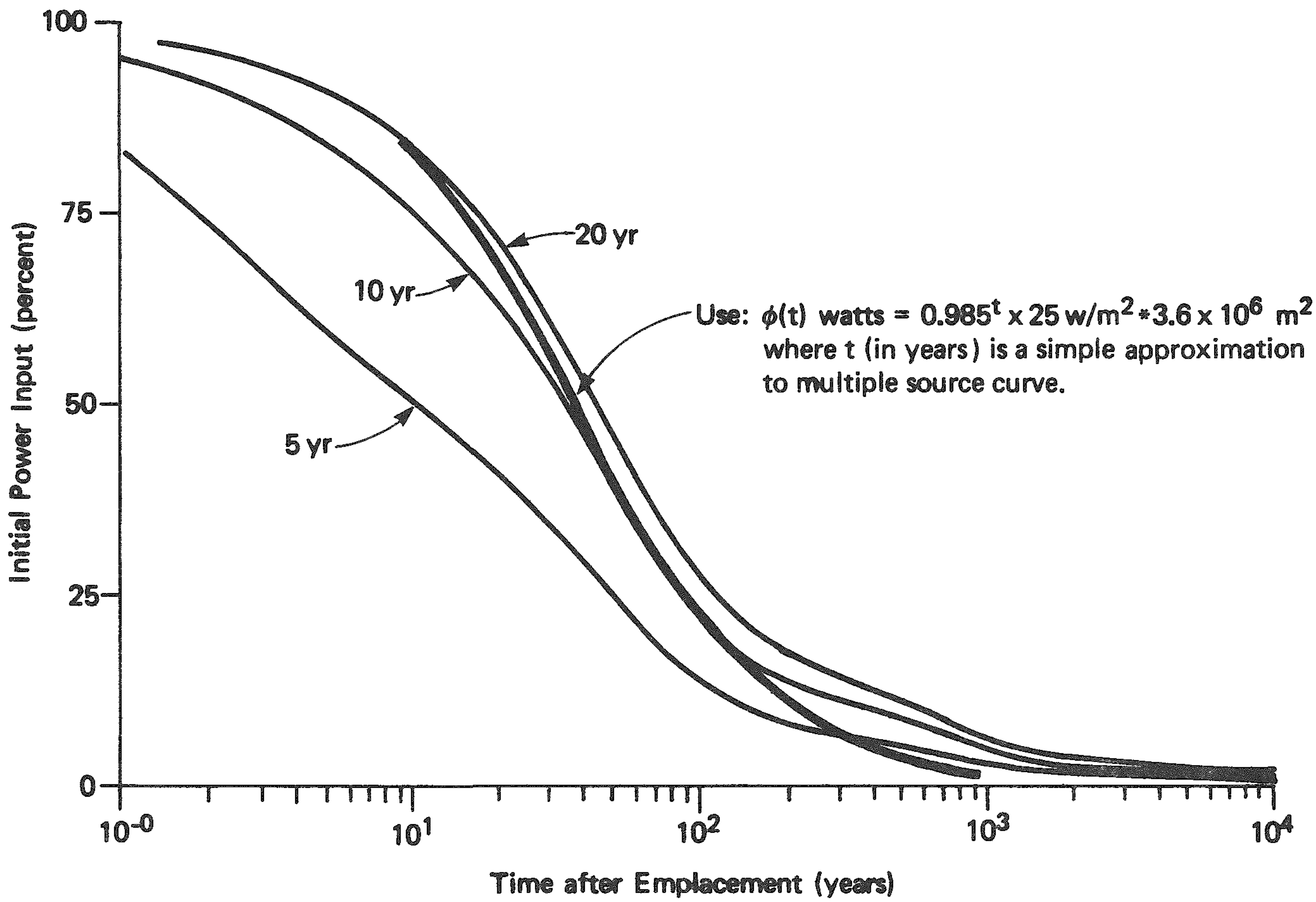
- High compressive boundary stresses around a plug near the repository;
- Tensile (or reduced compressive) boundary stresses around plugs at some distance above the repository; or
- Thermal stresses due to differential plug/wall rock expansion or uneven heating in the plug.

Hardy and Hocking in Rockwell (1980) used a gross thermal loading of 25 W/m^2 as a standard case for three repository shapes having total area of 3.6×10^6 m^2. The decaying power output of the heat source was typically modeled by a three-component source with up to 100-point or line heat sources used to model the distributed effect of the canisters.

Because the plugs will be at some distance from the repository, the following assumptions for heat transfer through the basalt are considered adequate for the purpose of plug modeling:

(1) Heat is generated from a point source (as illustrated in Figure 34);

(2) Heat is transferred by conduction through the basalt (ignoring heat transfer by fluid flow through the basalt); and



NOTE: Hardy and Hocking in Rockwell (1980) used multiple sources with power outputs of the form $\phi(t) = \sum^{N} a_n e^{-\lambda n t}$; N = number of components in source.

FIGURE 34

POINT HEAT SOURCE

(3) Temperature (T) at any point along the plug is defined by the following equation:

$$T(x,y,z,) = \frac{1}{8(\pi k)^{3/2}} \int_0^t \phi\,(t')e^{-r^2/4k(t-t')}\,\frac{dt'}{(t-t')^{3/2}} \qquad (3.3)$$

where

T	=	temperature
r^2	=	$(x-x')^2 + (y-y')^2 + (z-z')^2$,
(x',y',z')	=	location of point source
(x,y,z)	=	location of study point
$\Phi(t')$	=	heat flow rate
t'	=	time variable
t	=	time at study point
k	=	$K/\rho c$ = thermal diffusivity
K	=	thermal conductivity
ρ	=	average density
c	=	specific heat

(Carslaw and Jaeger, 1959)

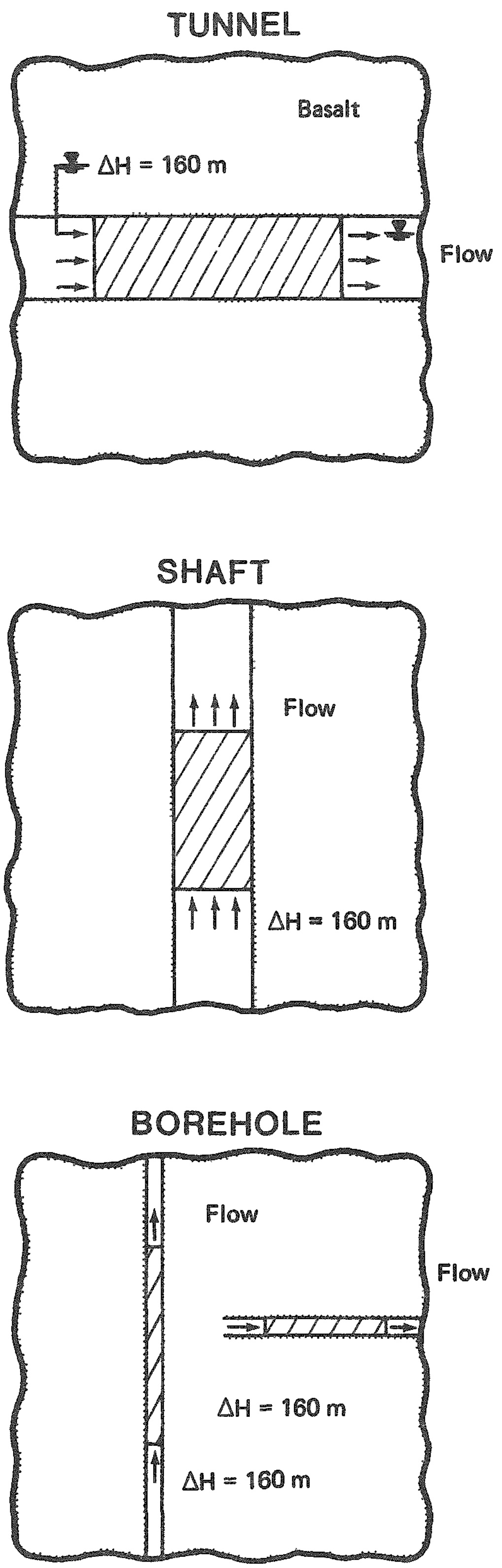
Ventilation of the repository will probably be necessary for its operation. Hardy and Hocking in Rockwell (1980) showed that ventilation can remove a substantial amount of heat from the repository, resulting in small temperature increases during the operation phase. We can assume that all tunnels and shafts used for repository operation will be ventilated. This may actually cause a slight increase in wall rock temperature in the shaft and tunnel walls, compared to the case where heat is transferred only by conduction in the basalt. Boreholes above the repository level, but not penetrating the repository, may also be affected by ventilation.

Wall rock temperatures will be maintained at less than 70°C during the operational phase and at less than 100°C during the retrievable storage phase (Rockwell, 1980) and suitable ventilation will maintain air temperatures that allow for men working underground on shafts and tunnels up to and during plug placement.

The initial temperature of the wall rock, its thermal conductivity, and the ventilaton and dewatering schemes will influence the maximum temperature that plugs may reach during curing. The heat of hydration generated during curing will cause the temperature of cement plugs to rise. After curing and upon cooling, substantial thermal stresses may develop in cement plugs and at the wall rock interface. Superimposed on the thermal cycling of plug curing will be the thermal cycling due to repository heat generation of the stored waste.

3.1.1.4 Modeling Conditions

In this problem definition process, it was decided to estimate the worst conditions that a plug might face. Then a variety of idealized tunnel, shaft, and borehole plug configurations were developed to facilitate the modeling process. Possible worst case conditions are shown in Figures 35 through 47 and, to simplify initial analysis, the 13 modeling conditions are spelled out (Table I). It should be emphasized that these figures represent current perception of worst cases. It may be desirable to revise or combine these cases upon further consideration of the repository operation and design.



PROBLEM:

Flow out of repository due to hot water.
NOTE: ΔH is the differential fluid pressure head acting across the plug, expressed in an equivalent height of water column at one end of the plug—typical, all modeling conditions.

DESCRIPTION:

During rewatering, at far end of plug, head equals a few meters. The repository (almost full) heats up:
P_{sat}, for water/steam system @ 200° C ≈ 160 m of water. Use post-plugging material parameters. Ignore temperature effect on materials.

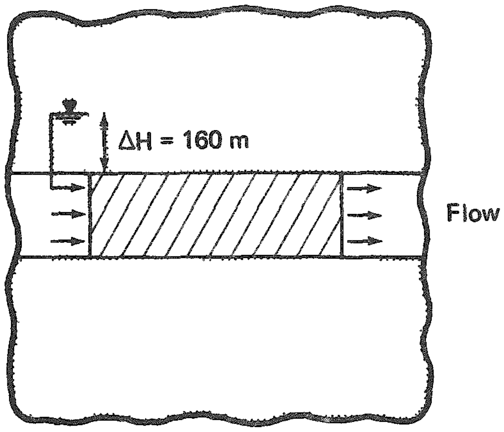
CONSEQUENCES:

Possibly unacceptable flow rate. Possible piping in plug.

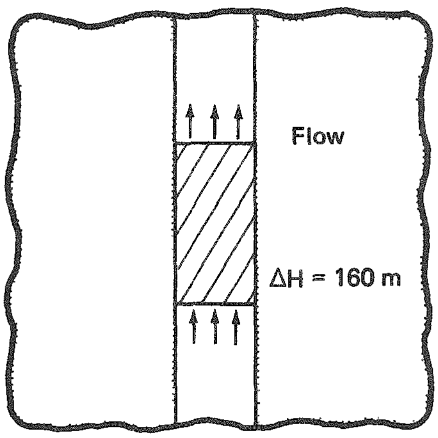
FIGURE 35

MODELING CONDITIONS NO. 1

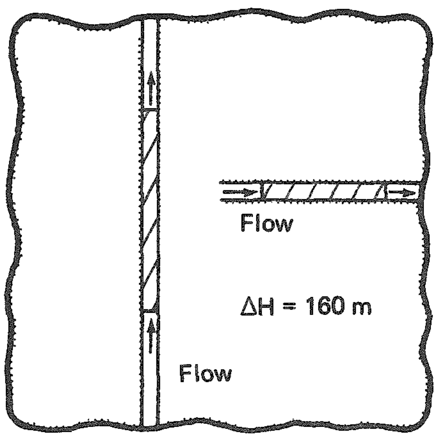
TUNNEL



SHAFT



BOREHOLE



PROBLEM:

Flow out of repository due to hot steam.

DESCRIPTION:

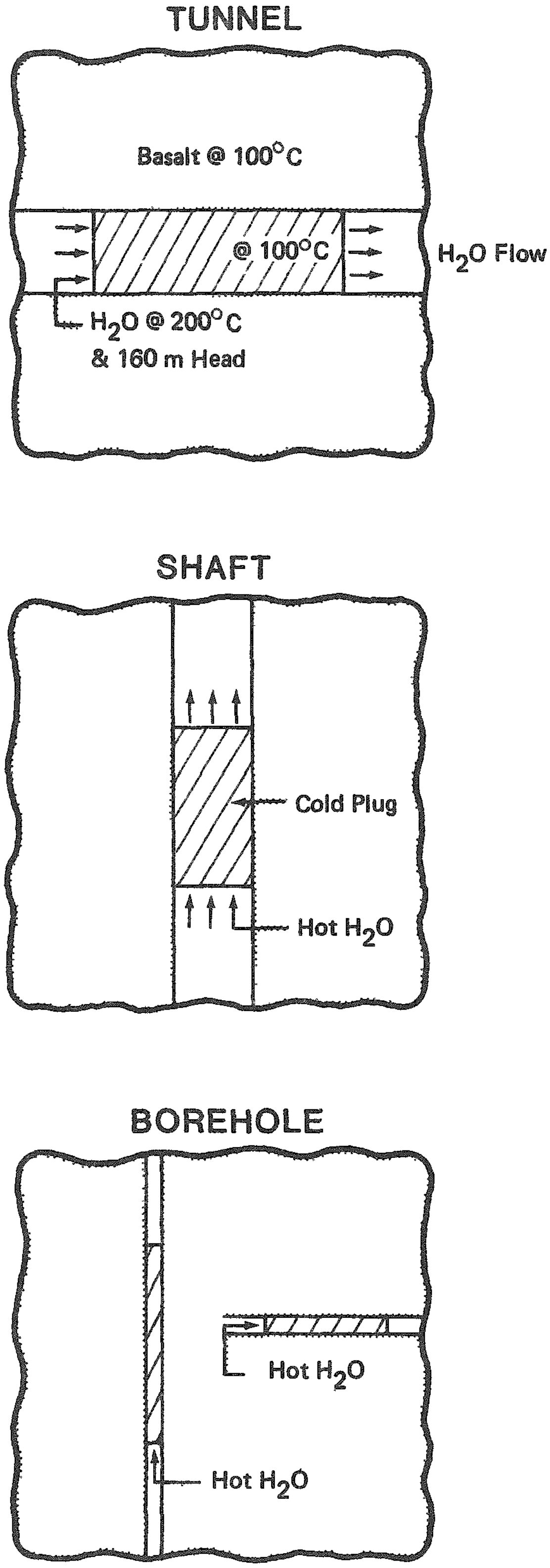
See Condition No 1. Pressure of steam will build up from about 25 cm @ 20°C to 160 m @ 200°C. Ignoring compressibility of steam, @ 200°C, $\frac{Q\ \text{stem}}{QH_2O} \approx 0.3$ (Q = flow rate) through a porous material.
Therefore, No. 1 is worse case, but steam flow might be considered. Analysis should consider compressibility.

CONSEQUENCES:

Possible unacceptable flow rate. May be offset by lower transport/capability of steam vs. H_2O.

FIGURE 36

MODELING CONDITIONS NO. 2



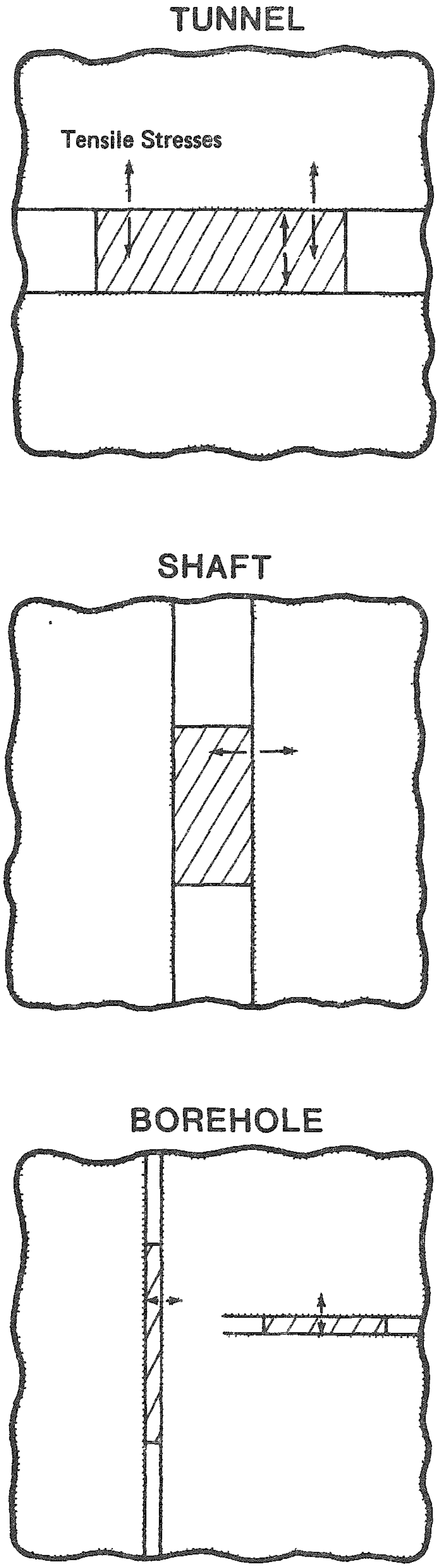
PROBLEM:
Thermal stresses in plug due to flow.

DESCRIPTION:
During and just after rewatering, convective flow brings hot H_2O to plug before heat conduction through basalt heats up plug. Assume $T_{wall} = T_{plug} = 100°C$, $T_{H_2O} = 200°C$. Heat flow into basalt and plug by conduction and by convection (i.e.,flow). Assess thermal stresses.

CONSEQUENCES:
Cracking due to thermal stresses may be possible.

FIGURE 37

MODELING CONDITIONS NO. 3



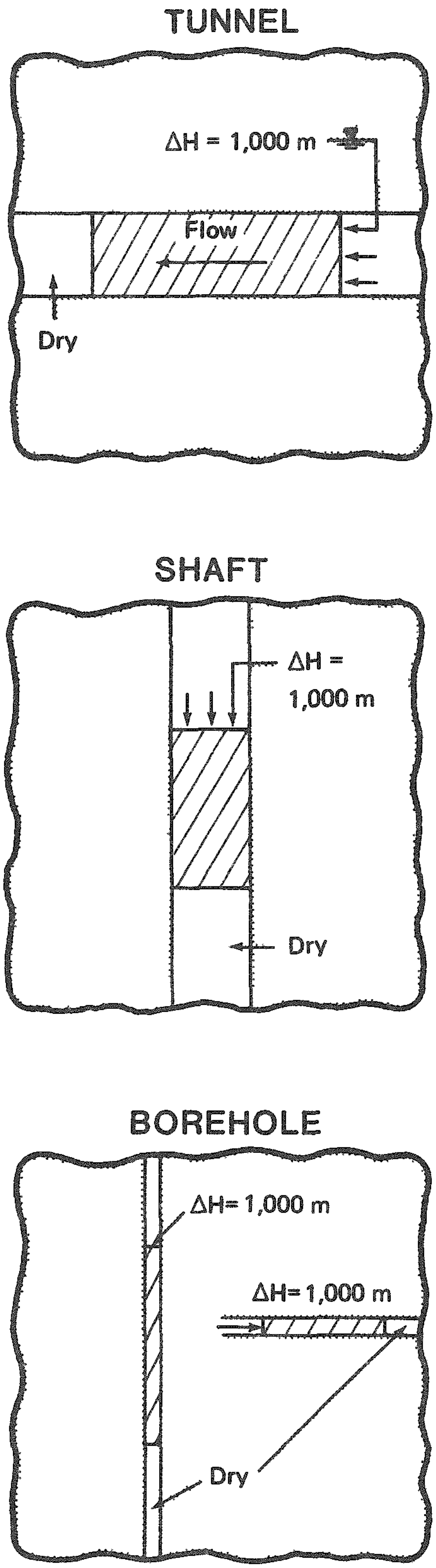
PROBLEM:
Cement plug contraction after curing.

DESCRIPTION:
Concrete or cement containing plugs will heat up during curing, especially if confined in a tunnel. Contraction upon cooling may produce tensile stresses in plug and across wall-rock interface.

CONSEQUENCES:
Possible cracking of plug or failure of bond at interface may produce a high permeability flow channel.

FIGURE 38

MODELING CONDITIONS NO. 4



PROBLEM:

Sliding stability of plug.

DESCRIPTION:

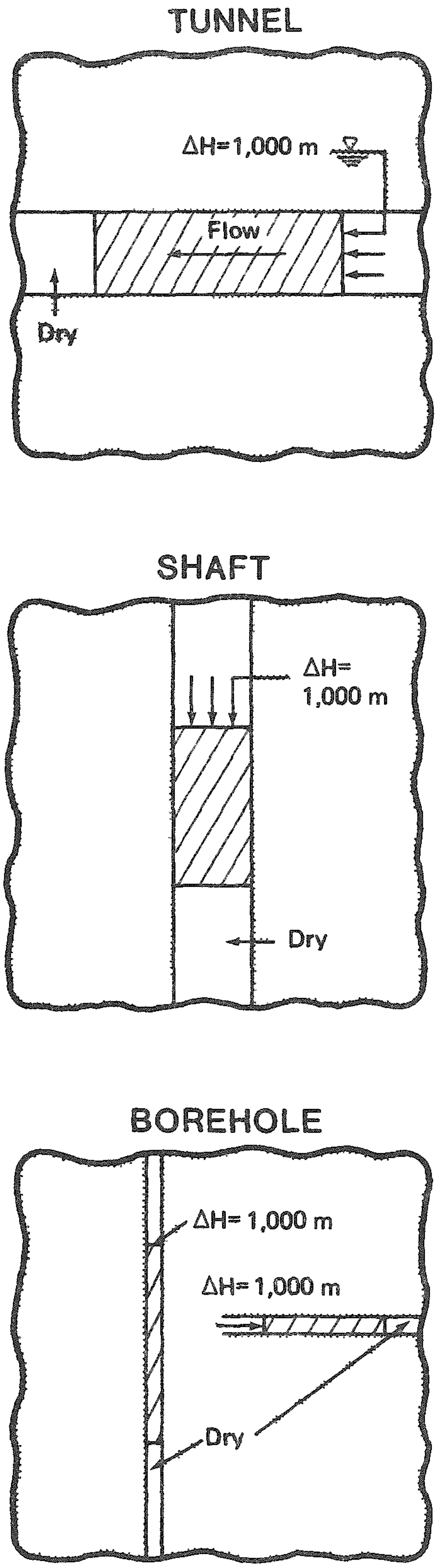
Shaft or borehole fills with water by connection with aquifer. Repository is dry. Assess resistance of plug to sliding against 1,000-m head. Note: flow into repository not critical unless it affects designed rate of rewatering.

CONSEQUENCES:

Plug may slide. Also check Factor of Safety against piping and hydraulic fracture.

FIGURE 39

MODELING CONDITIONS NO. 5



PROBLEM:

Flow stability of plug.

DESCRIPTION:

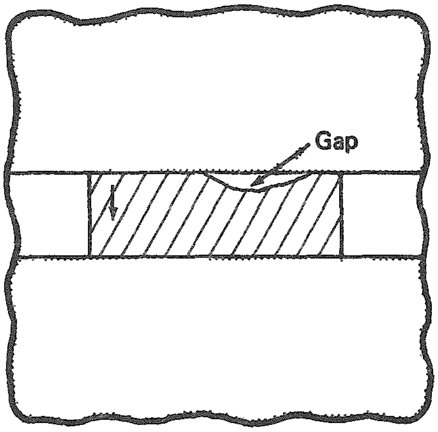
Same as for Condition No. 5.
Check for resistance against piping and hydraulic fracture.

CONSEQUENCES:

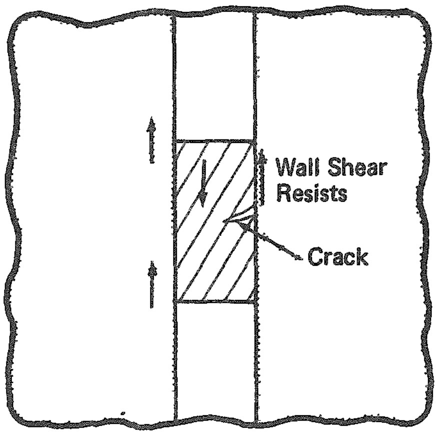
Plug may erode.
Unacceptable flow

FIGURE 40
MODELING CONDITIONS NO. 6

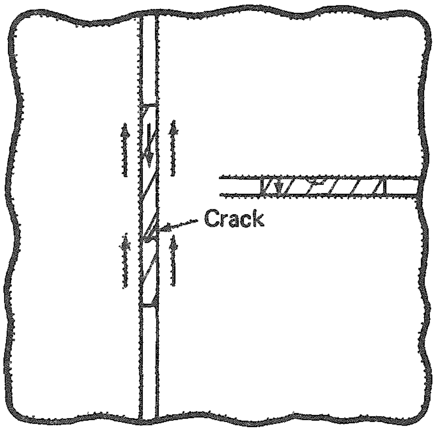
TUNNEL



SHAFT



BOREHOLE



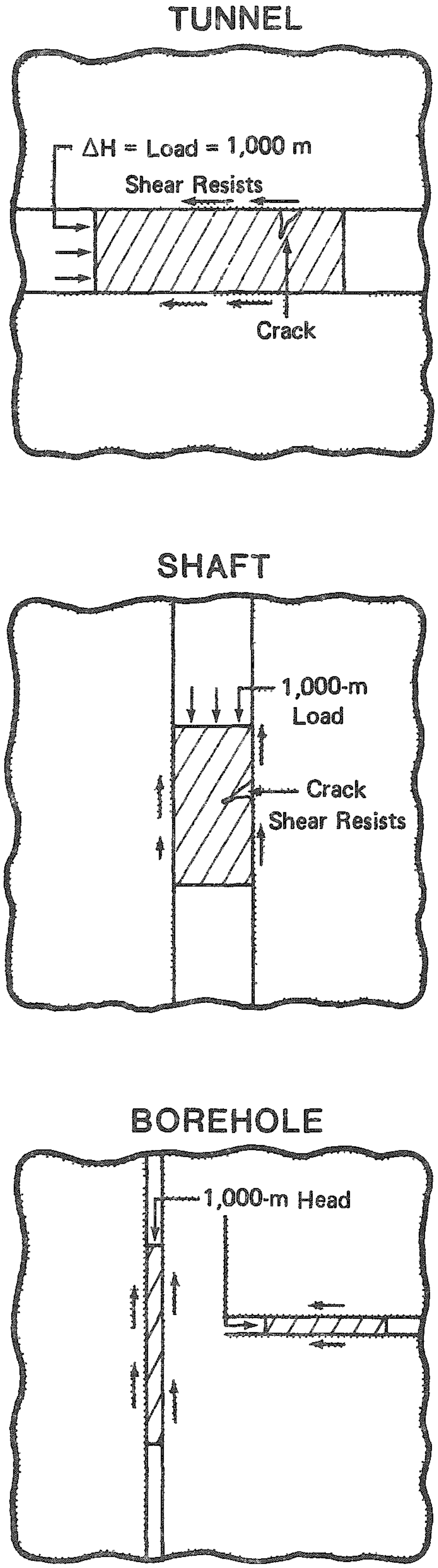
PROBLEM:
Plug consolidation under own weight.

DESCRIPTION:
After plugging but prior to rewatering, compressible plug consolidates under own weight.

CONSEQUENCES:
May leave gap in horizontal plugs and cracks in vertical plugs.

FIGURE 41

MODELING CONDITIONS NO. 7



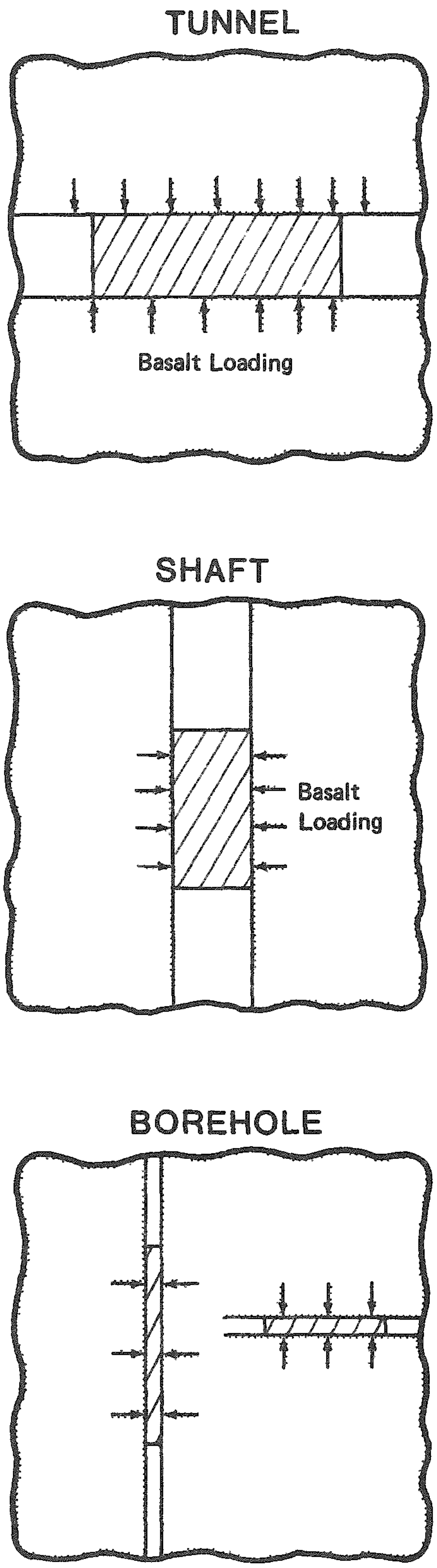
PROBLEM:
Plug consolidation under hydraulic load.

DESCRIPTION:
See Condition No. 5. Plug will see high head as a load. Assess consolidation under 1,000-m head

CONSEQUENCES:
Cracking may occur.

FIGURE 42

MODELING CONDITIONS NO. 8

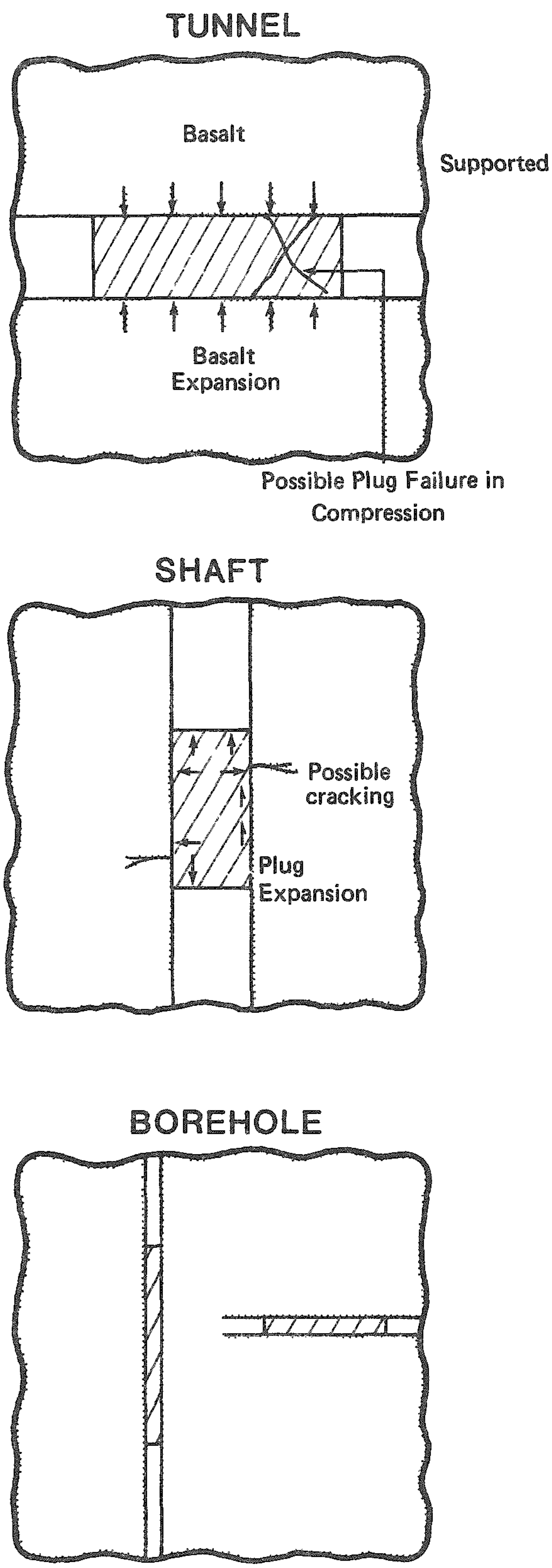


PROBLEM:
Plug compression under rock load.

DESCRIPTION:
If the wall rock supports are removed during plugging, then the plug must carry this load. Since rock load will decrease as strain allowed (up to equilibrium or instability), plug should be designed to carry a load compatible with a strain level that does not cause much loosening, thus resulting in an increase in permeability. Assess using rock load of 200 psi and 2,000 psi.

CONSEQUENCES:
Too weak of a plug will cause loosening and rock block fall out: high permeability in wall rock.

FIGURE 43
MODELING CONDITIONS NO. 9



PROBLEM:

Differential thermal expansion

NOTE: α is the thermal coefficient of expansion for a material.

DESCRIPTION:

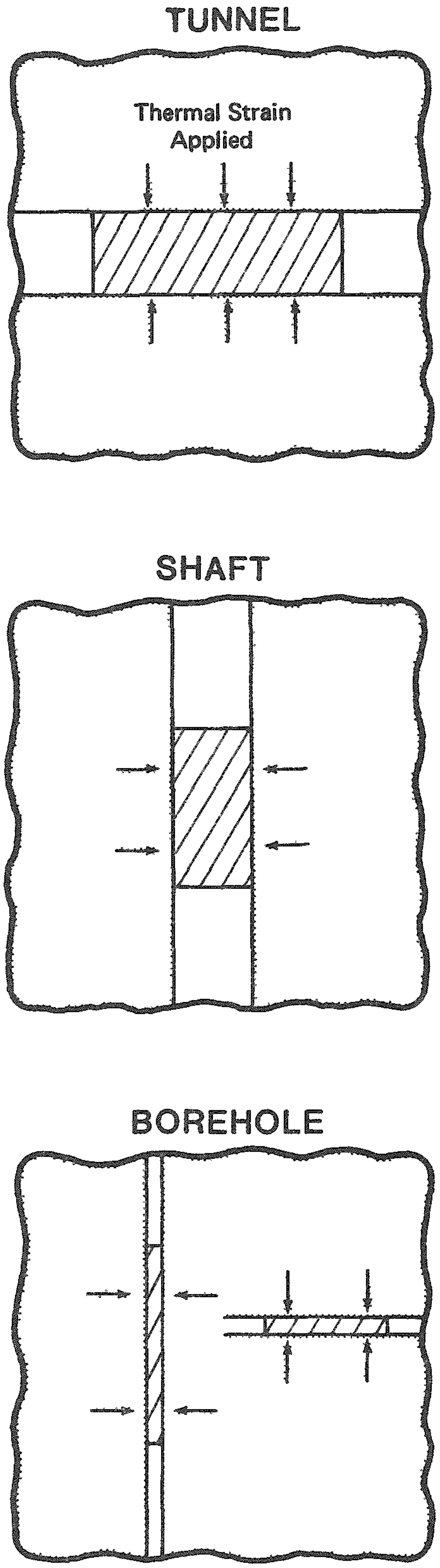
The plug will heat from ~ 70 °C to ~ 150 °C. If α of basalt and plug are different, stresses will result. Also, potential problems at ends of plug where basalt is unsupported or has a backfill of different α_T and E from plug. Also, if there is no end restraint on axial plug expansion, shear stress may be applied to basalt.

CONSEQUENCES:

Possibly (1) consolidation or creep of plug, leaving a gap when it cools; (2) cracking in basalt due to tensile hoop stresses if α_T plug > α_T basalt; or (3) compressive failure of plug.

FIGURE 44

MODELING CONDITIONS NO. 10



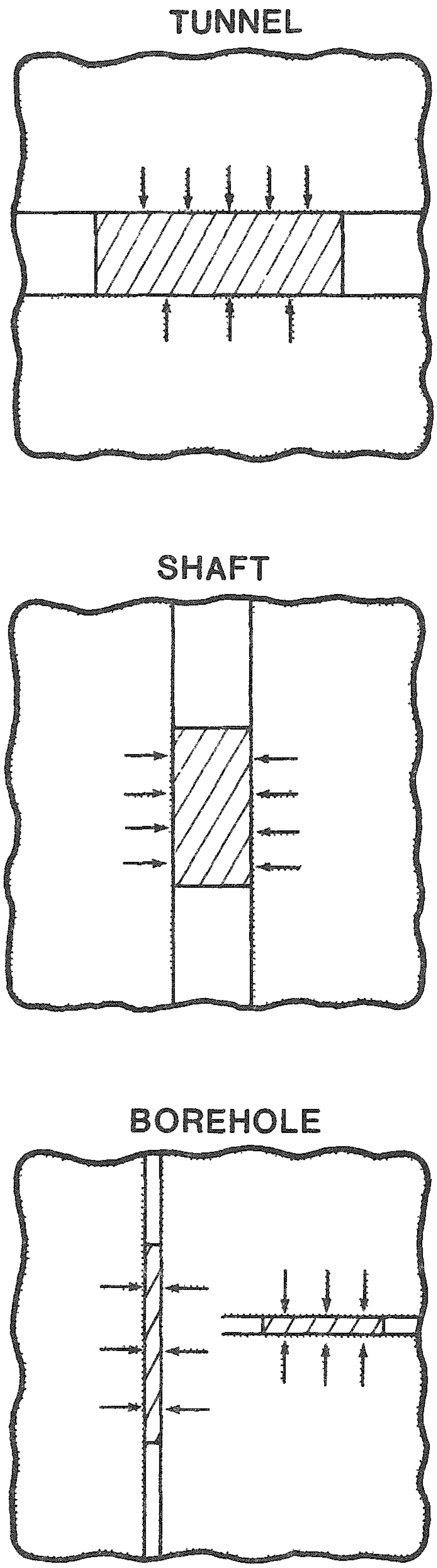
PROBLEM:
Non-recoverable plug compression due to thermal cavity closure.

DESCRIPTION:
Basalt cavity may narrow when heated and expand when cooled. This imposed strain will compress plug. Assess the recoverable deformation on cooling. Use 2 cases shown for Condition No. 9 as starting point. Include elastic and consolidation effects. Include grain crushing.

CONSEQUENCES:
Gap may form between plug and wall upon cooling, resulting in high flow.

FIGURE 45

MODELING CONDITIONS NO. 11



PROBLEM:

Long-term mechanical stability with decrepitation

DESCRIPTION:

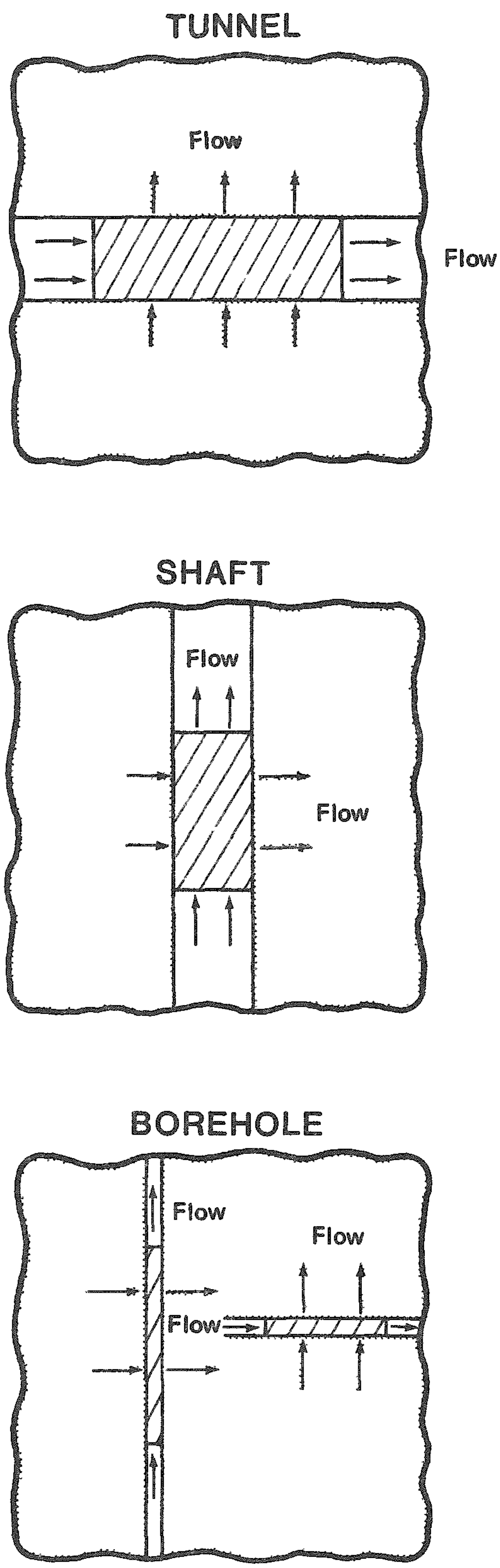
See Conditions No. 9; repeat but reduce strength; increase creep rate for wall rock and plug.

CONSEQUENCES:

Too weak of a plug will cause loosening and rock block fall-out, resulting in high permeability in wall rock.

FIGURE 46

MODELING CONDITIONS NO. 12



PROBLEM:
Long-term flow, with decrepitation.

DESCRIPTION:
Use 1 m/km horizontal gradient, 1 m/100 m vertical gradient. Increase permeability of plug and wall rock to allow for solutioning of joint-infilling and some erosion. Check piping against Factor of Safety.

CONSEQUENCES:
Possible unacceptable flow.

FIGURE 47

MODELING CONDITIONS NO. 13

TABLE I

MODELING CONDITIONS THAT MAY BE STUDIED

		Model Now with Simplified Material Parameters	Consider for Later Modeling
No. 1:	Flow out of repository due to hot water	●	●
No. 2:	Flow out of repository due to hot steam		●
No. 3:	Thermal stresses in plug due to flow	●	●
No. 5:	Sliding stability of plug	●	●
No. 6:	Flow stability of plug	●	●
No. 7:	Plug consolidation under own weight	●	●
No. 8:	Plug consolidation under hydraulic load		●
No. 9:	Plug compression under rock load		●
No. 10	Differential thermal expansion	●	●
No. 11	Non-recoverable plug compression due to thermal cavity closure	●	●
No. 12	Long-term mechanical stability with decrepitation	●	●
No. 13	Long-term flow with decrepitation		●

3.1.2 Numerical Analysis of Plug Seepage Control and Thermomechanical Performance

Preliminary numerical analysis involving closed form solutions was used to provide some insight into the effect of the zone of disturbed rock around an opening to be plugged, including an estimate of the lengths of plug necessary to achieve seepage control and the potential benefit of constructing cutoff collars that protrude from the plug into the zone of disturbed rock. A closed-form solution to the combined problem of thermomechanical behavior of a hard plug and the surrounding rock is used to evaluate the bond strength and confinement required for the plug to offset thermal stresses. Finally, in a critical review of these analyses, the limitations of closed-form solutions that treat separately the thermal, mechanical, and fluid dimensions of the problem and that assume gross simplifications (such as homogeneity, isotropy, and linear elasticity) are discussed. The possibilities for employing available computer programs, and the potential coupling of programs that treat separate aspects of the total thermomechanical-fluid flow problem, are also discussed.

3.1.2.1 Preliminary Analyses

The analyses were performed for quantity of seepage, sliding stability of plug, and thermal stresses in the plug. The allowable quantity of flow per year, as described in Design Criteria for Flow [Criterion (i)], was used for the seepage analysis, and a factor of safety of 1.5 was used for the sliding stability analysis. Thermally induced stresses were computed and then compared with the compressive strength of the plug. All the analyses are for an assumed diameter tunnel of

7 m. All other assumptions relative to the physical conditions of the plug environment are given in Appendix A.

Seepage Analysis

The quantity of water flowing through the plug system was computed using Darcy's law for flow through a porous media, which states:

$$Q = kiA \qquad (3.4)$$

where: Q = quantity of flow
k = coefficient of hydraulic conductivity
i = hydraulic gradient
A = cross-sectional area

For this analysis, flow was considered to be through the plug and disturbed basalt around the plug only, neglecting any flow through the undisturbed basalt. This is a valid assumption if the permeability of the plug and/or disturbed rock is significantly greater than that of the undisturbed rock.

The worse case condition for flow moving out of the repository is assumed to be a pressure head of 160 m of water, as shown in Figure 35. The flow is assumed to be steady-state, which means that the head has remained constant over a long enough period of time for the flow to stabilize, the plug is saturated, and phase changes are neglected. (The value of 160 m of pressure head is approximately the saturation pressure of steam at 200°C.)

The permeability of undisturbed basalt is estimated to range from 10^{-13} to 10^{-3} cm/sec, with an assumed value of 10^{-9} cm/sec for the basalt formation in which the repository will be constructed. Work by Iwai (1976) on the permeability of fractured basalt shows minimal changes in permeability for confining pressure above 5 MPa, while an increase in permeability by two orders of magnitude occurred when confining pressures were decreased from 5 MPa to 0. This would result in a permeability of 10^{-7} cm/sec for fractured basalt with low confining pressure. If the permeability was greater than 10^{-7} cm/sec, grouting might be able to reduce the permeability to 10^{-7} cm/sec. The thickness of the zone of fractured basalt around a plug is expected to depend greatly upon the construction techniques used for excavating and shoring of the tunnel; however, the stress relief around a circular opening can be approximated by the theory of elasticity (Timoshenko and Goodier, 1951).

For a uniform elastic material, a reduction in confining pressure from 28 MPa to less than 5 MPa would occur throughout a zone that has a thickness of less than 5 percent of the diameter of the tunnel; however, this reduction can only be considered to be the minimum estimate of the depth of rock disturbance because existing fractures, non-linear mechanics, and the construction method are not taken into account. Because the depth of disturbed rock is so difficult to evaluate, values ranging from 0 to 2 times the tunnel diameter were investigated in a parametric study.

Two values of permeability of the plug material were considered. The values of 10^{-8} and 10^{-9} cm/sec both fall within the range of permeabilities for concrete and laboratory-compacted clay. The lengths of a uniform plug required to limit seepage to 1 m^3/yr without cutoffs and for varying depths of the disturbed rock zone (DRZ) are shown in Figure 48 for a

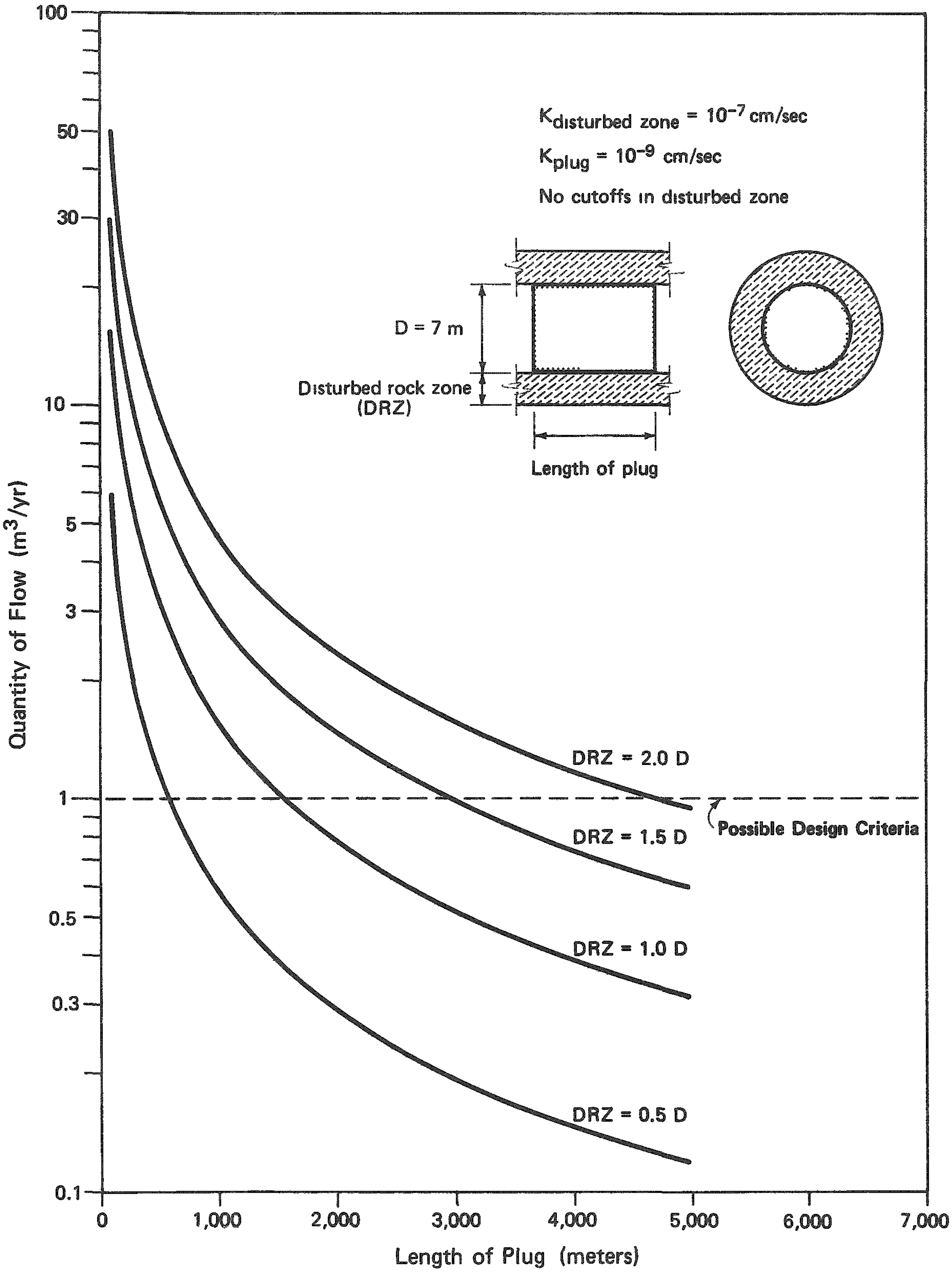


FIGURE 48

FLOW THROUGH PLUG OF PERMEABILITY 10^{-9} CM/SEC plug permeability of 10^{-9} cm/sec. Computations show that the length of plug necessary to meet the 1 m^3/yr criteria (assuming no disturbed rock zone surrounding that plug) would have to be 2 m for a plug permeability of 10^{-9} cm/sec and 20 m for a plug permeability of 10^{-8} cm/sec. The computation also shows that flow through a plug of either permeability is minimal compared with flow through the disturbed basalt. For a disturbed zone equal to the diameter of the plug (e.g., 21 m outer diameter boundary), a plug length of about 1,600 m would be necessary for either plug permeability.

These results indicate the importance of reducing the permeability of the disturbed zone and the inefficiency of requiring that the permeability of the plug material be more than an order of magnitude less than can be expected for the rock surrounding the plug. One way to reduce flow through a disturbed rock zone may be by installing cutoffs. Figures 49 and 50 show the results of computations evaluating the effectiveness of cutoffs equal to one-tenth of the total length of plug. For a disturbed zone equal to the plug diameter, the necessary length of plug with cutoffs is reduced to approximately 150 and 840 m for the respective permeabilities.

As summarized in Figure 51, the thickness and permeability of the disturbed zone are the major factors that influence the amount of flow. The results presented in Figures 43 to 51 were based on a tunnel diameter of 7 m. Flow through a 5-m tunnel would be approximately half and through a 10-m tunnel approximately twice that for the 7-m tunnel.

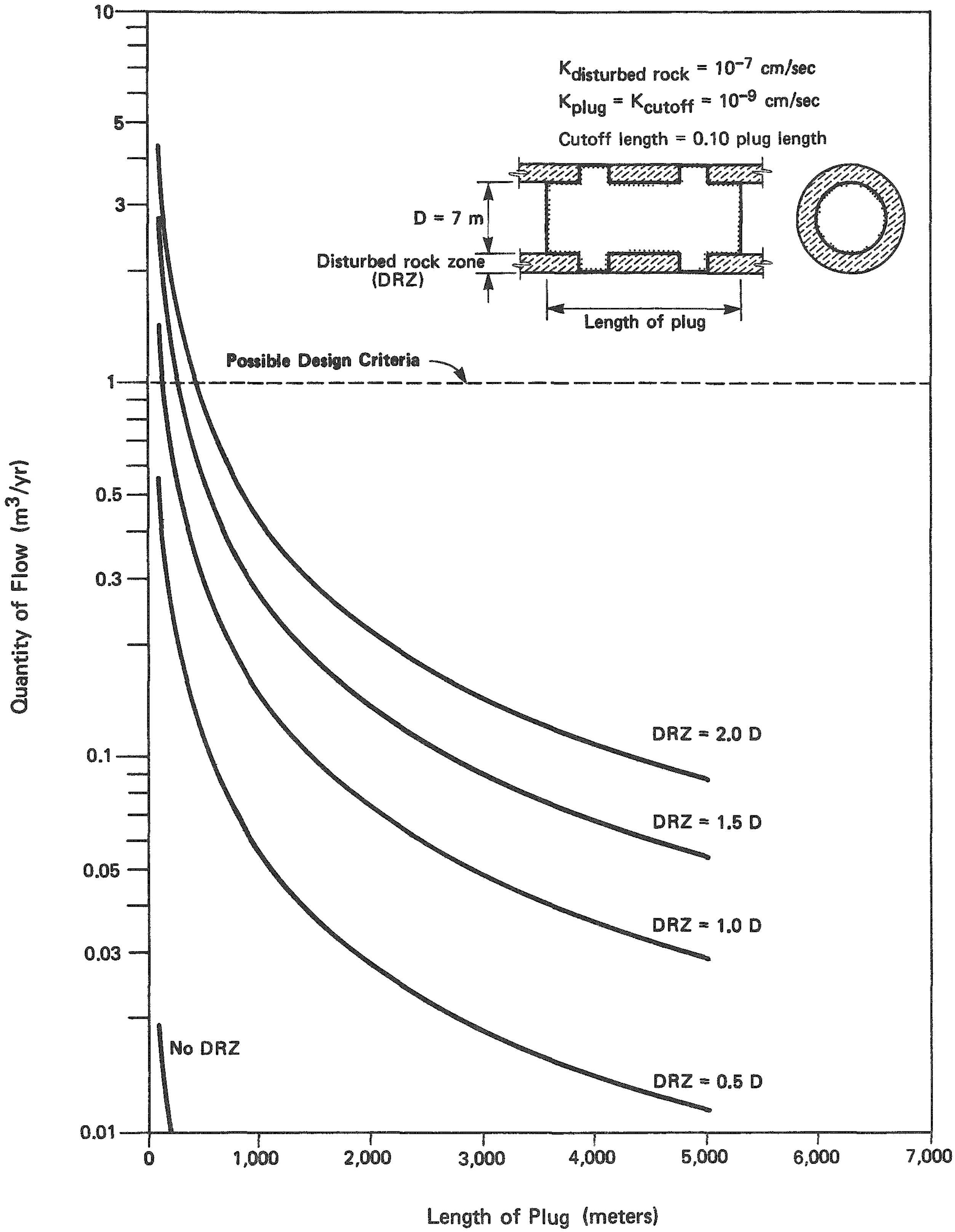


FIGURE 49

FLOW THROUGH PLUG OF PERMEABILITY 10^{-9} CM/SEC WITH CUTOFFS

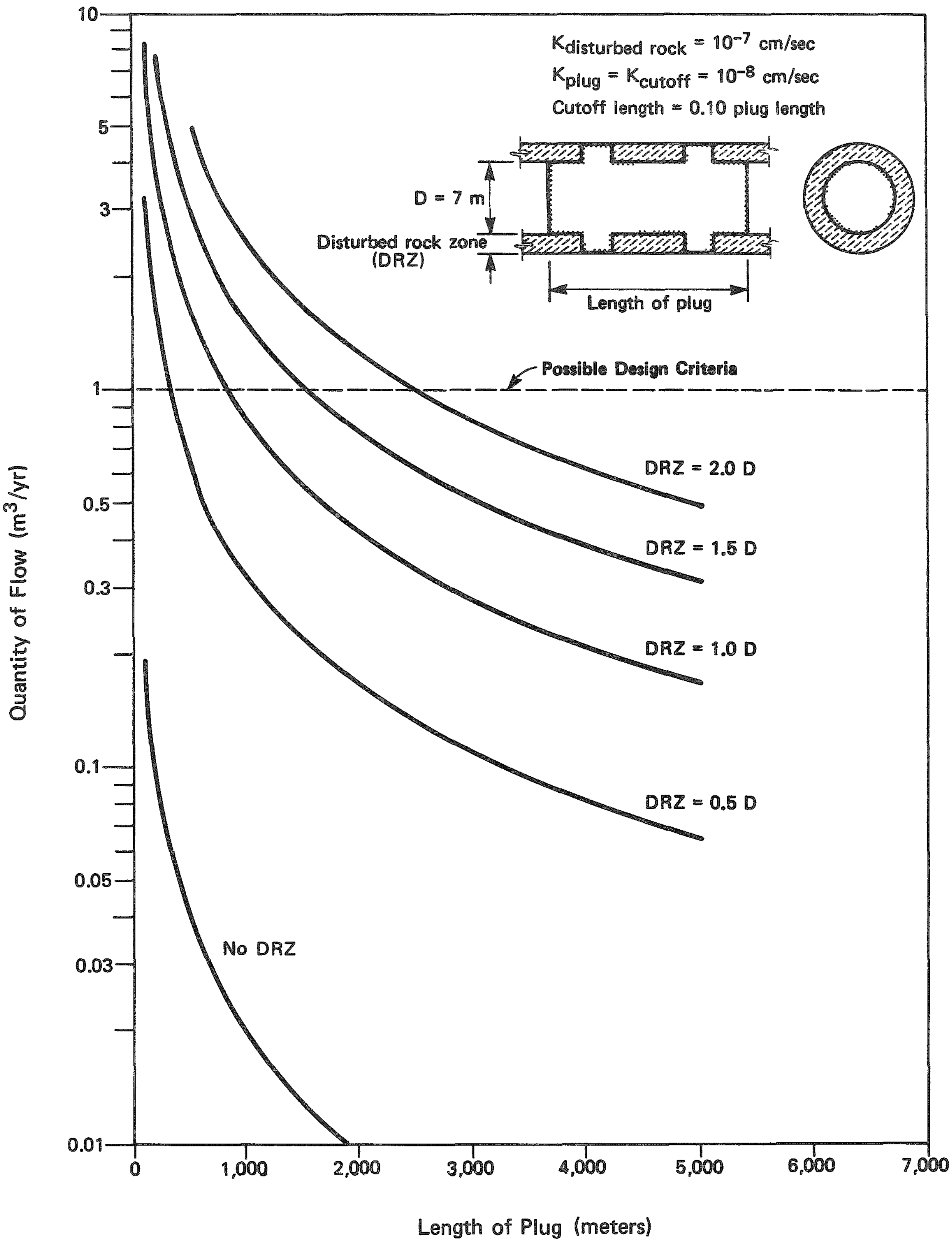


FIGURE 50

FLOW THROUGH PLUG OF PERMEABILITY 10^{-8} CM/SEC WITH CUTOFFS

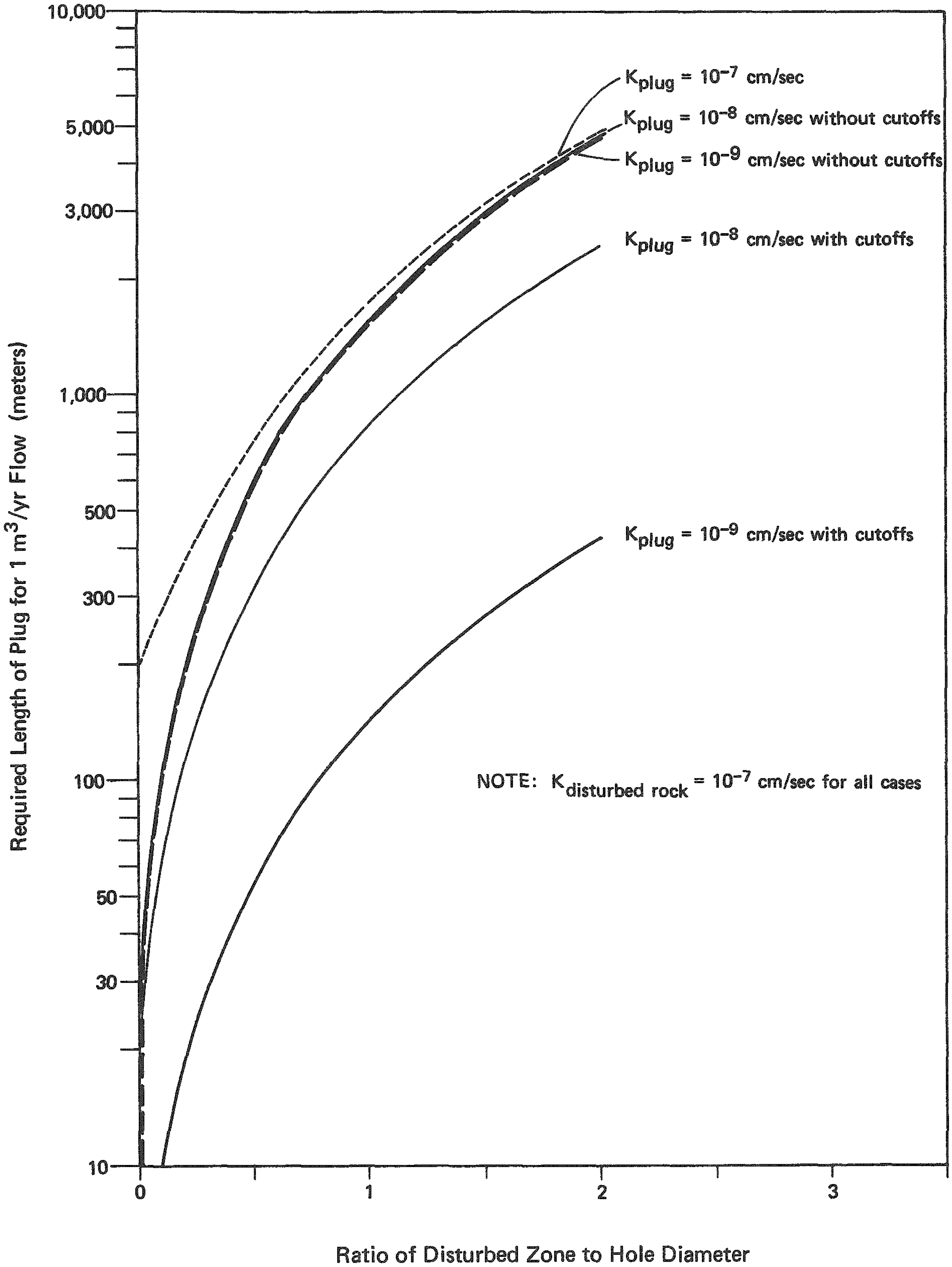


FIGURE 51

LENGTH OF PLUG
(IDEALIZED NUMERICAL MODEL)

Sliding Stability of Plug

The method used to assess the sliding stability of a plug was to compute the factor of safety against sliding (i.e., the shear strength of a possible failure surface divided by the stresses induced on it). For the purpose of these closed-form solutions, the failure surface was assumed to be the tunnel-plug interface, with the shear strength of the plug considered the controlling factor. The shear strength of disturbed basalt has not been established but is judged to be greater than the plug material strength.

The maximum driving force is assumed to be a pressure head of 1,000 m of water against the outside of the plug (1,000 m of water yields a pressure of 9.8 MPa). This models a condition in which the shaft fills with water before the repository has rewatered or significantly pressurized.

The shear strength of the plug, rock, and plug/rock bond all depend upon the confining pressure. The strength increases with increasing confinement, unless the confining pressure becomes so great that it changes the mechanical properties of the material (e.g., by breaking down its structure). The confining pressure of the plug is extremely difficult to estimate because it depends upon the support of the opening, amount of disturbance in rock, plug material, temperature, time, and method of placement. There is no simple way to evaluate the plug confining pressure, so a nominal value for plug shear strength has been used.

A representative value of the unconfined compressive strength of concrete is 30 MPa. The shear strength with no confinement is approximately 12 percent of this or 3.6 MPa. The necessary length of plug for a 7-m diameter tunnel with a factor of safety of 1.5 is only 7.15 m. This value is extremely conservative unless the force between the plug and tunnel wall is tensile, which could occur due to plug shrinkage (as in concrete curing) or temperature drop.

Clearly more detailed analyses of the strength of the plug must be made; however, based on this analysis, it does not appear that sliding failure of the plug will be the critical design factor. Analysis of the induced strains must also be done to check that flow paths are not established through shear zones within the plug.

Thermomechanical Stresses in Hard Plugs

An evaluation of the thermomechanical response of a plug and its environment was made using differential linear thermoelasticity to describe the behavior of the plug and the surrounding rock. The elastic solutions are developed (1) for a confined plug representing the case of a shaft plug or the case of a confined tunnel plug, where confinement is provided by an engineering designed structure (the term "confined" means that no axial movement of the plug is allowed); and (2) for an unconfined plug simulating the case of a tunnel plug that has an end free to move. A numerical application is given in the case of a concrete plug. The subscripts "p" for plug and "R" for surrounding rock are used to differentiate plug and surrounding rock elastic constants.

Elastic Modeling of the Plug/Host Rock Medium

In this analysis, the plug and surrounding rock are assumed to be perfectly homogeneous, isotropic, and elastic and can be mathematically described using the theory of differential linear elasticity. When determining thermal stresses, the temperature change is taken as uniform and equal to 50°C throughout the plug and the host rock. Solutions for the elastic, host rock-plug problem are provided using the Saint Venant principle (Timoshenko and Goodier, 1951); i.e., the solutions for the elastic stress field distribution caused by the lithostatic stress field around a circular hole are solved separately and superimposed onto the solutions for the thermoelastic stress field induced in the plug and its environment by a uniform increase in temperature. The thermoelastic stress field for the plug/host rock system is determined using equations developed by Timoshenko and Goodier (1951) to describe the thermal response of the plug (a long, solid cylinder) and the thermal response of the surrounding rock (a long, thick-wall hollow cylinder). The condition of radial displacement compatibility at the plug/rock interface provides the necessary equation to resolve the problem.

The lithostatic stress with the basalt at a depth of 1,000 m is assumed to be hydrostatic and is estimated to be 28 MPa prior to repository excavation, based on the values given in Appendix A. Moreover, both shafts and tunnels are assumed to be 7 m in diameter for the purposes of this analysis. Elastic constants for the basalt are based on values assumed in Appendix A:

E_R (Young's Modulus) = 77×10^3 MPa;

V_R (Poisson's Ratio) = 0.25;

a_R (thermal expansion coefficient) = 6.2×10^{-6}/°C.

Elastic constants for the concrete are based on laboratory test data for this project and on assumed thermal coefficient:

E_p (Young's Modulus) = 30×10^3 MPa;

V_p (Poisson's Ratio) = 0.20;

α_p (thermal expansion coefficient) = $10^{-5}/°C$.

Stress Distribution Around a Circular Opening

Elastic solutions for the stress distribution around a circular hole have been given by Obert and Duvall (1967) for long shafts or tunnels. The equations describing the stress field at any distance from the hole boundary are given by:

$$\sigma r_R = \frac{Sx + Sz}{2}\left(1 - \frac{a^2}{r^2}\right) + \frac{Sx - Sz}{2}\left(1 + \frac{3a^4}{r^4} - \frac{4a^2}{r^2}\right)\cos 2\theta \quad (3.5)$$

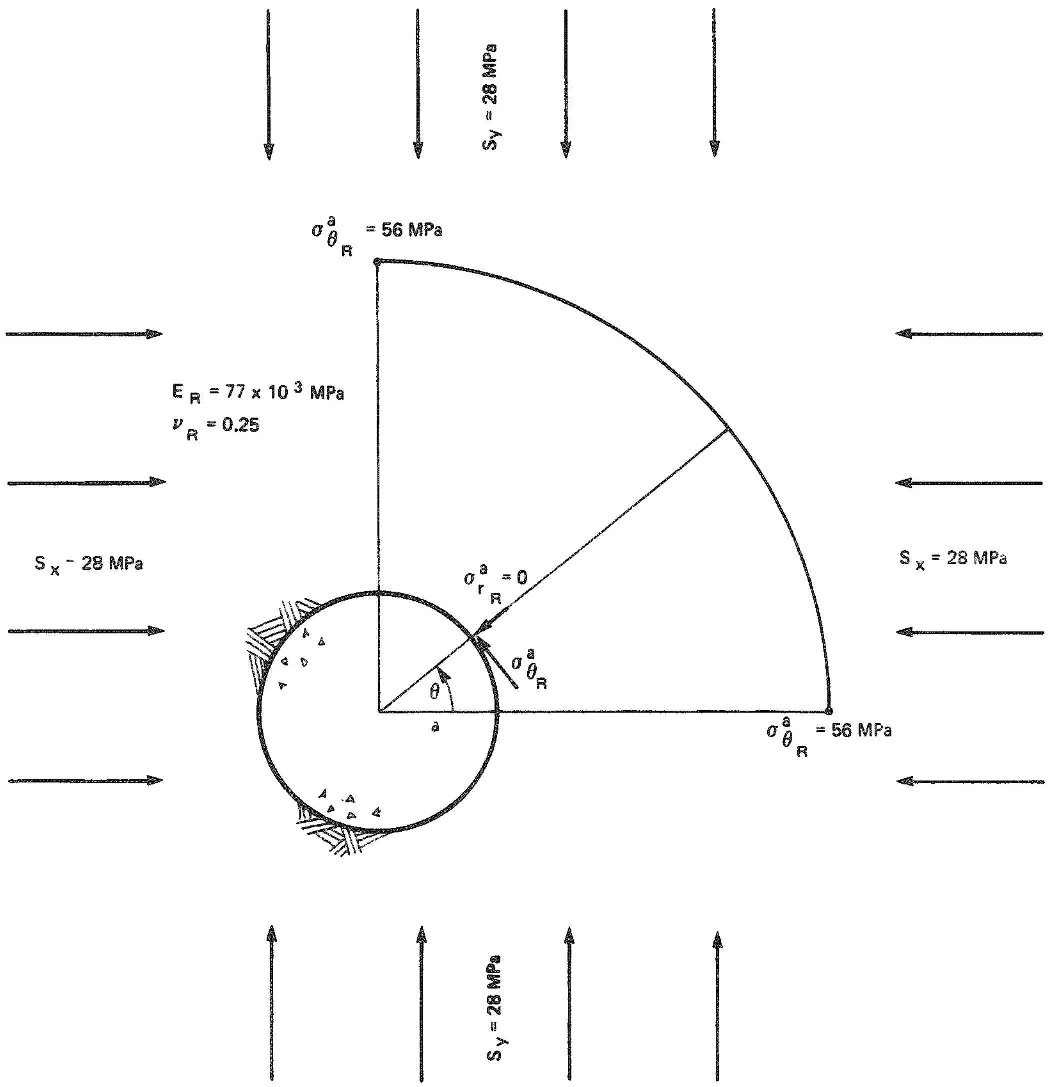
$$\sigma\theta_r = \frac{Sx + Sz}{2}\left(1 + \frac{a^2}{r^2}\right) - \frac{Sx - Sz}{2}\left(1 + \frac{3a^4}{r^4}\right)\cos 2\theta \quad (3.6)$$

$$\tau r \theta_R = -\frac{Sx - Sz}{2}\left(1 - \frac{3a^4}{r^4} + \frac{2a^2}{r^2}\right)\sin 2\theta. \quad (3.7)$$

Numerical application using a 28 MPa hydrostatic, lithostatic stress field leads to a uniform tangential stress of 56 MPa at the hole boundary, as shown in Figure 52.

Thermal Stresses in a Confined Elastic Plug and its Environment

A solution is based on an assumed condition of radial displacement continuity at the plug/wall rock interface. The development of the following equations is shown in Appendix B:



NOTE :

Elastic solution for a homogeneous, isotropic, elastic basalt medium under hydrostatic, lithostatic stress.

At the plug/wall rock interface, $r = a$, $\sigma^{a}_{r_R} = 0$,

$$\sigma^{a}_{\theta_R} = 56 \text{ MPa for all } \theta \text{, and } \tau^{a}_{r\theta_R} = 0$$

FIGURE 52

STRESS DISTRIBUTION AROUND TUNNEL AND SHAFT

- State of stress on the plug

$$\sigma_{\theta_p} = \sigma_{r_p} = P \quad (3.8)$$

$$\sigma_{z_p} = 2\nu_p P - E_p \alpha_p T. \quad (3.9)$$

- State of stress in the surrounding rock at the plug/wall rock boundary (r = a)

$$\sigma_{r_R}^{a} = P \quad (3.10)$$

$$\sigma_{\theta_R}^{a} = -\frac{2\alpha_R E_R T}{1 - 2\nu_R} - P. \quad (3.11)$$

Equations 3.8 and 3.9 indicate that the state of stress is the same everywhere in the plug and could readily be simulated or modeled in a standard triaxial test arrangement.

The numerical analysis in the case of a concrete plug leads to the curves shown in Figure 53. For an increase in temperature of 50°C, the radial and tangential stresses inside the plug reach 34.2 MPa. However, the confining axial stress σ_{z_p} is 28.7 MPa. Therefore, the plug is only submitted to a stress differential of 5.5 MPa. The isotropic part of the stress field (28.7 MPa) is certainly not strong enough to cause a failure of the concrete by crushing while the stress differential is less than 20 percent of the unconfined compression strength of the concrete (30 MPa).

Thermal Stresses in an Unconfined Elastic Plug

In this section, the term "unconfined" means that no forces are acting at the end of the plug to restrain any potential axial

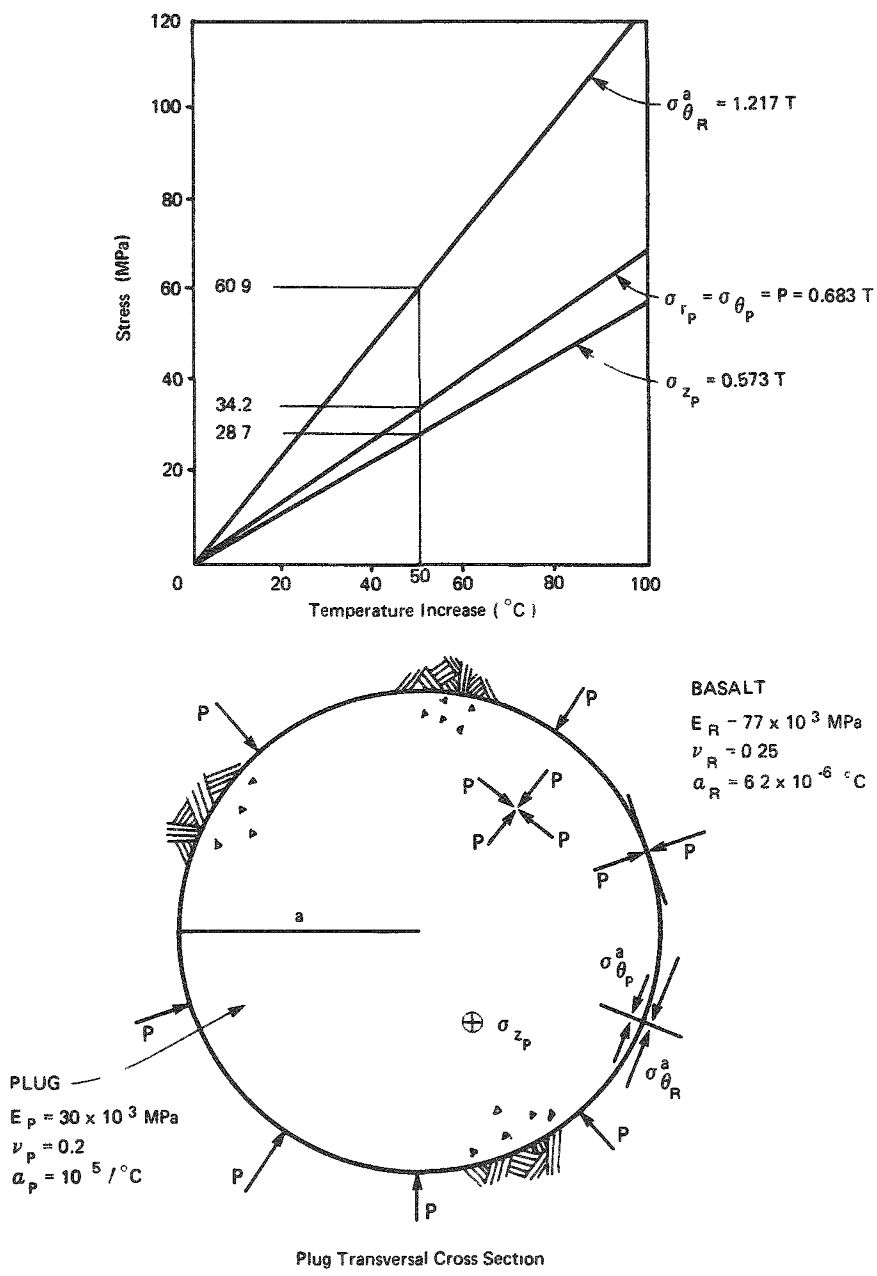


FIGURE 53

THERMOELASTIC RESPONSE OF A CONFINED CONCRETE PLUG movement so that $\sigma_{z_p} = 0$. In this case, the state of stress in the plug is given by (as developed in Appendix B):

$$\sigma_{\theta_p} = \sigma_{r_p} = P \qquad (3.12)$$

$$\sigma_{z_p} = 0. \qquad (3.13)$$

As in the case of the confined plug, the state of stress is the same everywhere in the plug. However, no confinement is provided to help offset the radial load. In Equation 3.12, the radial stress P takes into consideration this modification in boundary conditions. Although identical to Equation 3.8, its algebraic formulation is slightly different from the case of a confined plug (see Appendix C).

The numerical analysis in the case of an unconfined concrete plug leads to the curves shown in Figure 54. For a 50°C increase in temperature, the radial and tangential stresses inside the plug reach the value of 29.7 MPa. Because no confinement is provided, the radial stress must be directly compared with the unconfined compressive strength of the concrete (30 MPa), so that the resulting safety factor is on the order of 1.0 (see the discussion of safety factors in Section 3.1.1.2).

To avoid any differential axial movement at the plug/wall rock interface, the bond strength between the plug and the wall rock should be strong enough to resist the thermal shear stresses induced by the difference in thermal expansion properties of the plug and the rock. An algebraic formulation of the axial thermal stress at the interface is given in Appendix B. As shown in Figure 54 (curve "b") for an increase in temperature of 50°C the required bond strength reaches 11.2 MPa which is

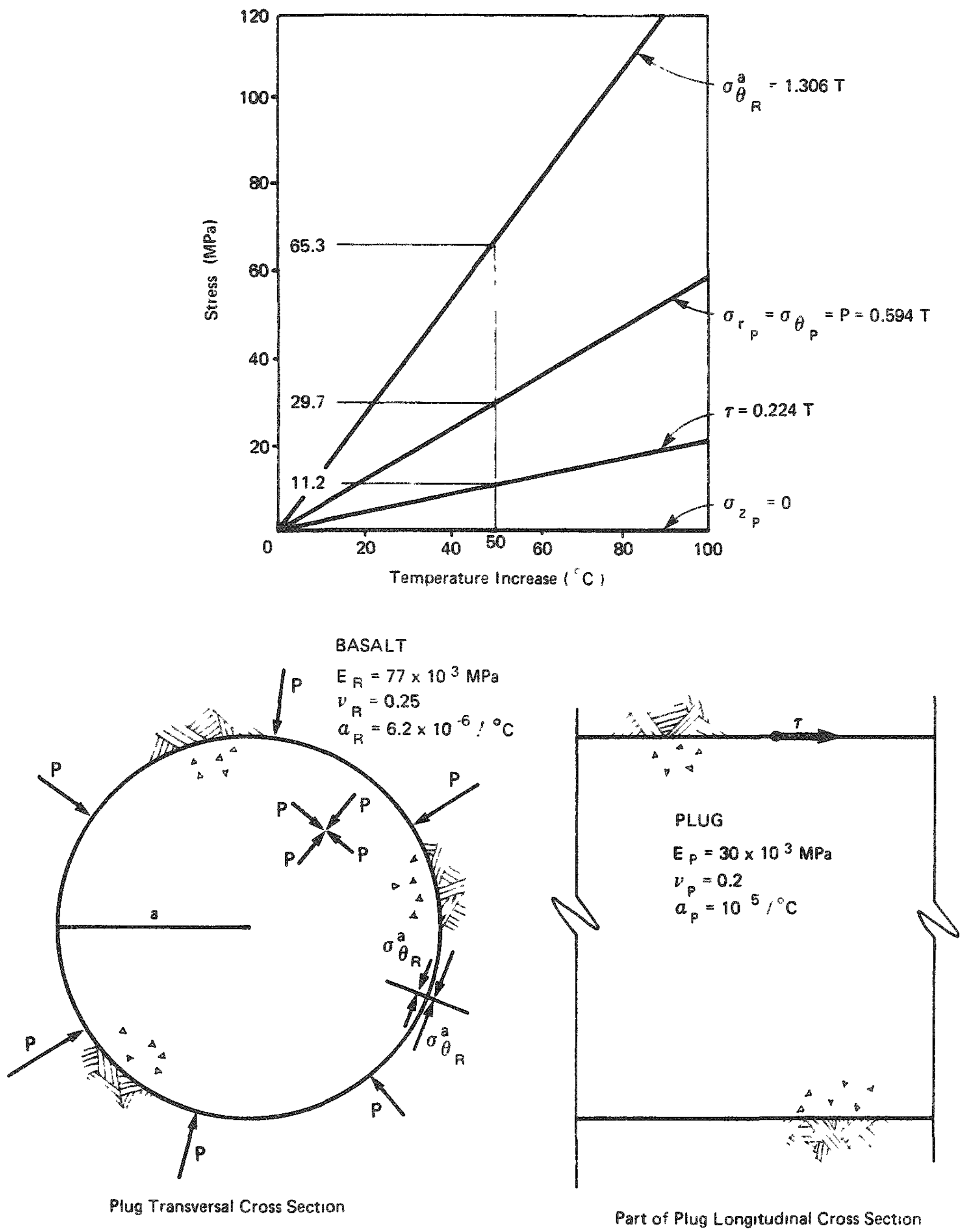


FIGURE 54

THERMOELASTIC RESPONSE OF AN UNCONFINED CONCRETE PLUG more than twice the expected value of the bond strength of concrete (approximately 5 MPa, based on laboratory test data).

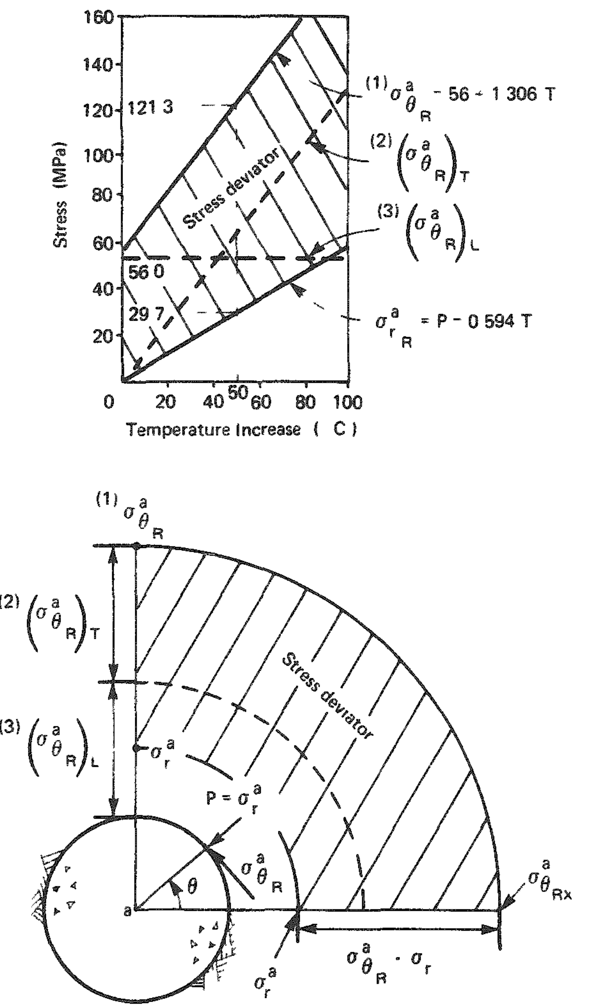
Thermomechanical Stress in the Surrounding Rock at the Plug/Wall Rock Interface

Elastic solutions for the thermomechanical stress field in the surrounding rock were obtained by superposition of the stress associated with the lithostatic stress field and the thermal stress induced by temperature increase. Solutions for a confined and an unconfined plug are very similar so that the analysis for an unconfined plug can be applied as an approximation for a confined plug.

Results for the superposition of thermal and lithostatic stresses are given on Figure 55. For a 28-MPa hydrostatic lithostatic stress field and a temperature increase of 50°C, radial and tangential stress at the plug/wall rock interface are given by

$$\sigma_{r_R}^{a} = 29.7 \text{ MPa} \ ; \ \sigma_{\theta_R}^{a} = 121.3 \text{ MPa}.$$

The stress deviator $\sigma_{r_R}^{a} - \sigma_{\theta_R}^{a}$ (i.e., 91.6 MPa) is approximately a third of the assumed basalt unconfined compressive strength (218 MPa). However, in this computation, the deterioration of the rock by stress relief and loosening is not taken into consideration, and the assumption of a hydrostatic state of stress in the repository before mining is not the most conservative assumption. Calculations (not reported herein) show that, for a high horizontal lithostatic stress (Sx = 50 MPa, Sz = 28 MPa), the stress deviator of the tangential compressive stress at the plug/wall rock interface reaches 158 MPa.



NOTES

(1) $\sigma^a_{\theta_R}$ = Total tangential stress in the rock at the plug wall rock interface $\sigma^a_{\theta_R} = \left(\sigma^a_{\theta_R}\right)_T + \left(\sigma^a_{\theta_R}\right)_L$

(2) $\left(\sigma^a_{\theta_R}\right)_T$ - Tangential stress in the rock at the plug/wall rock interface caused by thermomechanical loading

(3) $\left(\sigma^a_{\theta_R}\right)_L$ = Tangential stress in the rock at the plug/wall rock interface caused by lithostatic stress relief

FIGURE 55

THERMOMECHANICAL STRESSES IN THE SURROUNDING BASALT ROCK AT THE PLUG INTERFACE

Conclusions

All analyses performed in this section were based on models containing many idealized conditions and on judgmental values for material properties. This has been useful for obtaining a preliminary overview of the general nature of the problem, but more detailed analyses using more sophisticated models must be performed before the actual designs are possible.

The results from the preliminary seepage analysis show that plug materials that have permeabilities in the range of clays and concrete could be used. It is not really useful to design the permeability of the plug more than an order of magnitude less than can be expected in the surrounding rock. The extent of the disturbed zone is significant and should be minimized as much as possible. This may lead to limitations on the use of blasting in the area of the plug. Cutoffs in the zone of disturbed rock can be effective in reducing seepage.

The failure of the plug by sliding is probably not a problem but cannot be ruled out because the simple analysis performed contains so many uncertainties.

Modeling of the plug and surrounding rock system should ultimately be made, including more realistic design parameters to describe the disturbed zone and the use of a thermoelasto-plastic law to simulate the hard plug and rock behavior. However, the study of the perfectly elastic plug in competent basalt does furnish guidelines for plug scheme evaluation.

For a 50°C increase in temperature, 7-m diameter concrete plugs have to be confined (1) to sustain the radial thermomechanical loading; and (2) to avoid bonding failure at the concrete/wall rock contact caused by occurrence of significant thermal shear stress along the bonding surface. In the case of a shaft, confinement is naturally provided by the overlying shaft backfill pressure. In the case of a tunnel, confinement should be provided by engineering design or by increasing the length of the plug so that part of it is outside the limits of the 50°C temperature increase. In this case, the bond strength of this part of the plug provides confinement for the rest of the heated plug length.

3.1.2.2 Computer Solutions

(This section of the report discusses how the analyses of plugs may be aided by mathematical modeling and computer solutions of performance phenomena. Some available computer programs that may be adapted to this purpose are reviewed.)

The nuclear waste repository may be constructed at depths of some 1,000 m in the basalt flows of the Columbia Plateau. Canisters containing the toxic nuclear waste will be placed in the repository during a storage period, following which there will be a retrievability period which is estimated to last between 25 to 50 years, at the end of which the storage rooms will be backfilled for structural support and all borehole, shaft, and tunnel accesses will be sealed. The repository is maintained dewatered and ventilated during the entire storage and retrievability period, at the end of which natural rewatering is allowed to occur.

During the waste isolation period, the temperature in the repository will slowly increase, causing an increase in temperature in the neighboring rock mass. Hot water or vapor flow may occur due to the convection process induced by temperature gradients and also due to the seepage process induced by hydraulic gradients. Simultaneously, the thermal gradient in the rock masses will induce stress changes that can also influence the water flow. The three interacting phenomena involved are:

(1) Fluid flow;
(2) Heat flow; and
(3) Stresses and deformation.

These phenomena are coupled in the following ways:

- Coupling through stresses or strain:

  (a) The permeability coefficient depends on the state of stresses. The thermally induced and excavation-induced stress changes will alter the flow and, hence, the temperature distribution.

  (b) The thermal conductivity can be influenced by rock strain. Changes in the strain will affect the porosity and hence, the moisture content and thermal conductivity. Therefore, the thermal conductivity is stress dependent.

  (c) Rock failure within the rock mass, such as tensile cracking or joint sliding, will cause changes in the thermal conductivity and permeability.

- Coupling through constitutive relationships:

  (a) The stiffness properties of the materials may be temperature dependent. These effects are small for basalt rock but may be important for clays, concrete, and other candidate materials for the plug.

(b) The stiffness properties of clay materials are affected by the pore water pressure and, hence, may depend on the flow pattern.

Some important considerations in the analysis of the plug are:

- The sequence of excavation and placement of the tunnels and shafts, as well as the construction techniques and system of support, should be accounted for in determining the initial state of stresses.
- The stress analysis should be carried out for anisotropic, non-homogeneous materials accounting for the initial state of stresses and the thermal gradients.
- Information regarding the state of stresses around the excavation should be sufficiently detailed to allow for stability analysis of the rock around the openings.
- Rock discontinuities (such as joints or faults) must be taken into account.
- Thermal analyses must consider material anisotropy and non-homogeneity and allow for temperature dependent material properties.
- Thermal gradients may produce tensile stresses in the rock mass. Because jointed rock cannot sustain tension,

a non-linear rock behavior eliminating the tensile stresses must be incorporated.

- Coupling of the rock permeability and the state of stresses must be considered.

- The heat transfer due to ground water may influence the temperature and stress distributions.

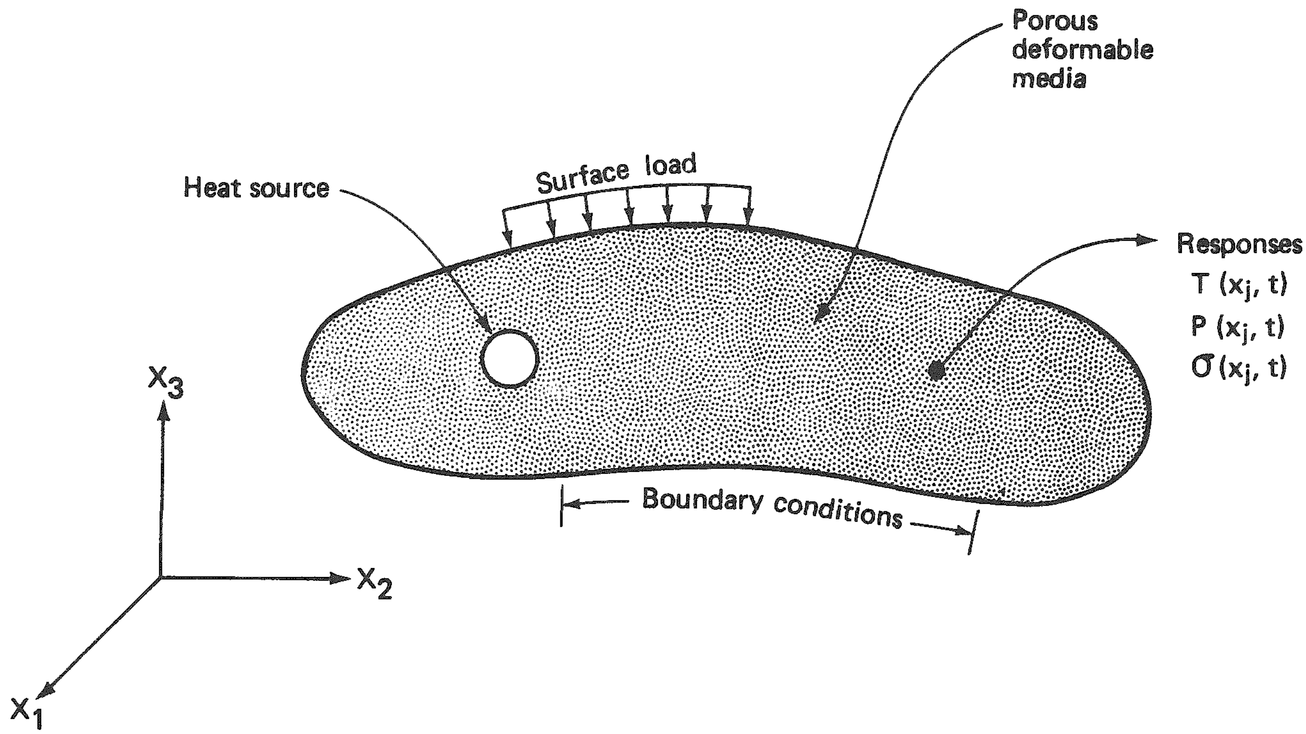
This section investigates the computational techniques necessary to determine the performance of a plug in connection with these important thermo-hydromechanical problems.

Review of Available Methods of Analysis

In this section, a summary review of the available methods for the numerical evaluation of the response parameters governing the thermal-hydro-mechanical phenomena is represented. The objective is to calculate the temperature-induced and pressure-induced stresses and deformations in multi-phase media consisting of solid, liquid, and gas that are subjected to a mechanical and thermal environment, as is shown schematically in Figure 56. A schematic classification of the available modeling techniques is presented in Figure 57.

(i) Analytical Methods

There is a considerable body of literature concerning closed-form solution for steady state or non-steady state temperature distribution in solids. Mitchell and others (1978) summarized a list of closed-form solutions pertaining to the temperature distribution in the ground from a heat source (point source).



From Rahman and Kao (1979)

FIGURE 56

THE GENERAL PROBLEM

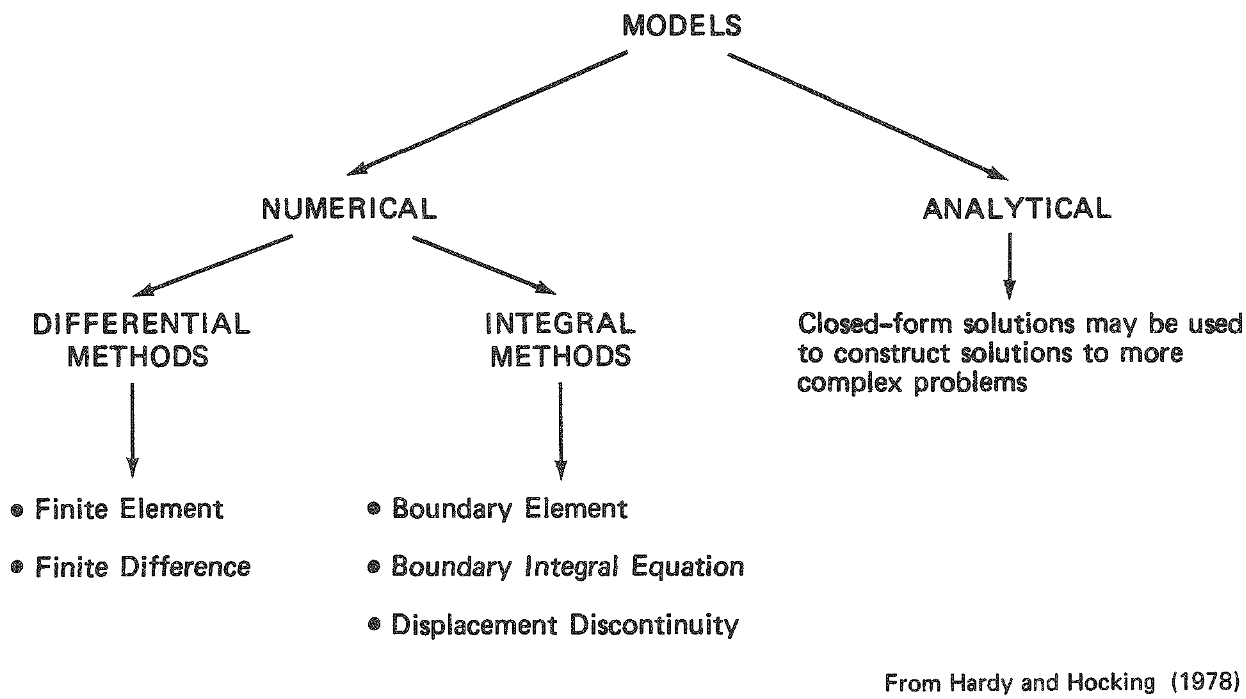


FIGURE 57

THERMOMECHANICAL MODELING TECHNIQUES

There is also a large collection of equations for temperature distribution in solids published by Carslaw and Jaeger (1959). Point, line, and cylindrical heat sources were considered. Solutions for anisotropic materials may be obtained by appropriate transformations.

Solutions for thermomechanical problems are less well developed. They are given for the cases of instantaneous point and line sources in an infinite region by Nowaki (1962). They can be integrated with respect to time to obtain solutions for constant and exponentially decaying sources. These analyses are useful for regional studies, but they are limited by their assumption of linear behavior material.

(ii) Numerical Methods

These methods involve certain approximations for the purpose of modeling the existing inhomogeneities, discontinuities, and non-linear material behavior, as well as the coupling between heat flow, fluid flow, and mechanical response.

The differential methods may use the finite element technique or the finite difference technique. In the first method, the region is divided into a number of elements that provide a physical approximation to the original continuum, and an exact solution to the physically approximated problem is obtained. In the second method, the governing differential equations are approximated directly, and the approximation is mathematical rather than physical.

Differential methods can be used to solve both boundary value problems and initial value problems. In connection with the latter, the time-stepping algorithm can be carried out implicitly or explicitly. Explicit formulations are easier to handle and any material behavior can be incorporated; however, the formulations need to limit the time step in order to maintain numerical stability. Implicit formulations require a greater computational effort, but they are unconditionally stable (e.g., independent of time-step size). For slow phenomena, such as heat conduction, the implicit method with large time increments is entirely adequate.

(iii) Boundary Integral Methods

In these techniques, only the boundaries of the region under study are to be defined, and no numerical approximations are made within the region to be simulated. When applied to the solution of elasticity problems, fictitious forces or displacement at the boundaries are used to obtain the stresses and deformations at any point. Such methods can be used to model non-homogeneous materials, elastoplastic behavior, joint opening and slippage, non-linear deformation properties, and 2-D and 3-D analysis. In general, it is possible to solve uncoupled fluid flow and thermomechanical problems by the boundary integral method.

A Method of Analysis

For a detailed analysis of the thermo-hydromechanical problem, a proposed flow chart is presented in Figure 58, and a discussion of the different steps is as follows:

(i) Initial Stress Analysis

Data accumulated on the behavior of basalt indicate that the tunnel geometry, the elastic stress relaxation (and hence, the

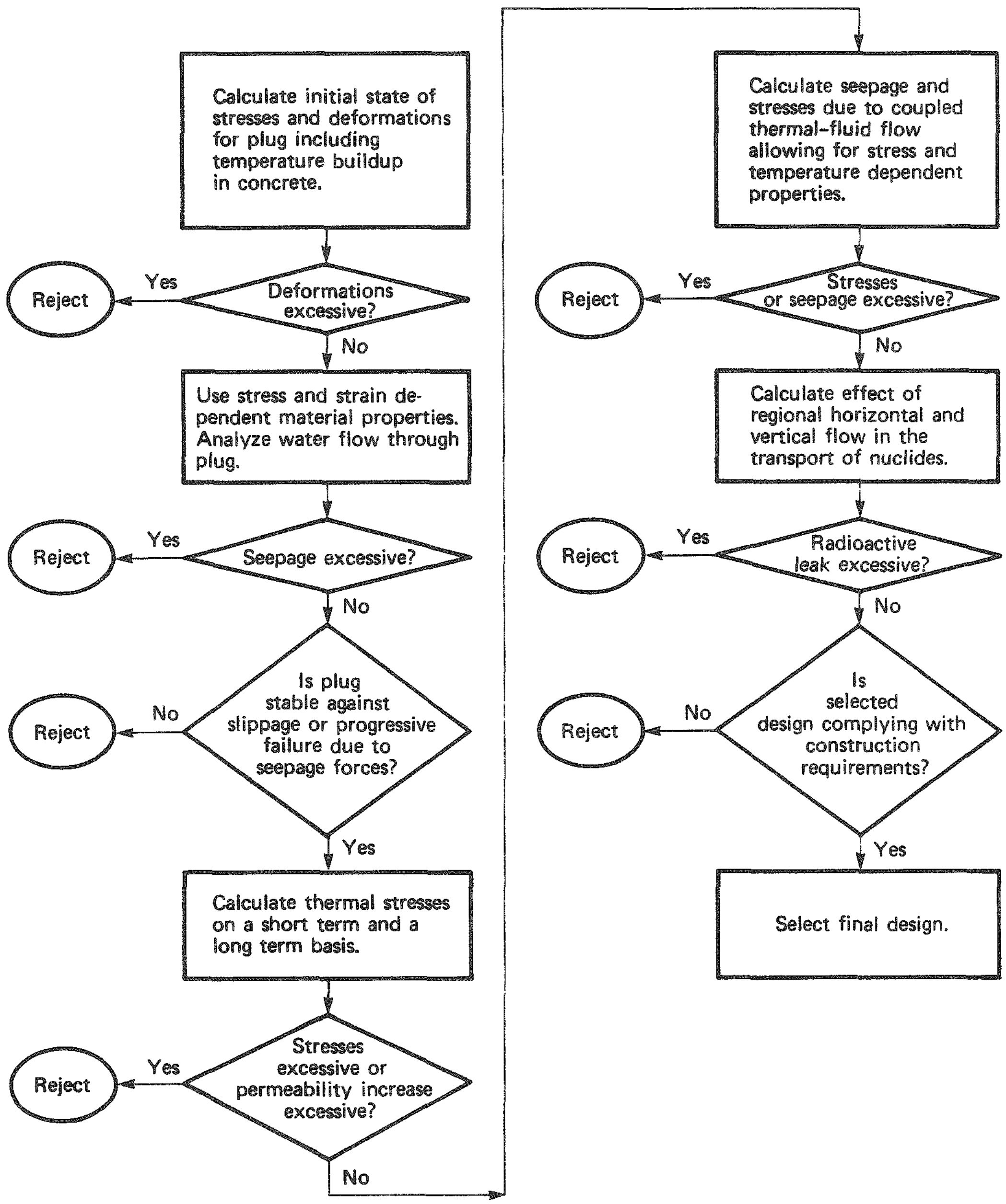


FIGURE 58

PROPOSED FLOWCHART FOR DETAILED PLUG ANALYSIS excavation procedures), the tunnel liner and support installation (Schwartz and Einstein, 1978), and the removal of support and plugging are controlling factors in the distribution of stresses around an excavation. Also, the possible influence that randomly and uniformly distributed joints will have in the material properties must be considered, in particular, the influence of a disturbed zone. Analytical and empirical methods can be used to incorporate any in-situ data and obtain a better determination of the initial stress distribution around the plug. Where in-situ measurements are lacking, stress distributions having different horizontal stress/vertical stress ratios, such as presented in Figure 33, may be considered.

Once the initial state of stresses on the plug is determined, programs DAMSWEL and NONSAP* can be used to model the non-linear deformation of the plug/wall rock system in 2-D and 3-D geometry, respectively. This analysis may be supplemented by computations using FINEL, CDC/ANSYS, CDC/MARC, or STEALTH to account for long-term deformations, including the presence of randomly or uniformly distributed joints in the wall rock and the creep properties of the plug.

The possible consolidation of the plug under its own weight can probably be avoided by careful control during construction. A detailed computation to analyze this effect may not be necessary.

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* See Table II for explanation of codes.

(ii) Thermal Stress Analysis

There are many aspects of the thermal stress analysis of the tunnel-plug and shaft-plug systems. An important aspect is to carry out comparative thermal-stress computations, assuming that the thermal flow and the fluid flow are uncoupled for simplicity. Later, fully coupled analyses may be conducted.

Simplified thermomechanical analysis can be carried out with program SALT3, which uses the displacement continuity method to model the regional distribution of thermal stresses around the tunnel. Factors of safety against rock slippage can be obtained to predict any significant change in joint opening and the subsequent increase in permeability.

Detailed parametric analysis of the tunnel-plug or shaft-plug system must be conducted to assess the influence of different variables, such as:

- Intensity and distribution of thermal loading;
- Depth of installation;
- Basalt properties;
- In-situ stress ratios;
- Tunnel or shaft geometry; and
- Retrievability period and initial thermal conditions on the candidate plug materials.

However, these parameters may well be reduced to only a few, once the details of the repository become better known.

Both longitudinal as well as cross-sectional geometry can be considered. Ideally these analyses must consider anisotropy, non-homogeneities, temperature-dependent properties, and material discontinuities, such as both ubiquitous and isolated joints, non-tension stress computation, and strain-dependent thermal properties. Previous results of thermomechanical behavior of repositories (Hardy and Hocking in Rockwell, 1980) show that the behavior of basalt is probably thermo-elastic, but behavior of the plug materials is not yet resolved.

Because the temperature changes will be slow and because of the difference in the thermal expansion coefficients of the wall rock and the plug material, there are two important stages in the process of stress distribution. During the first stage, the temperature is increasing, and the equilibrium state of stresses is reached as the wall rock and the plug try to expand against each other. During the second stage, as the radioactive waste cools down and the temperature decreases, the wall/rock and the plug will slowly return to their initial temperatures but not necessarily to their initial state of deformations. The time intervals of analysis must be long enough to allow for these two stages to happen, and the material characterization must be specified in such a way as to allow the detection of conditions such as joint slippage, crack openings, etc., which may produce a significant increase in the seepage of radioactive fluids.

There are several codes that can be used for detailed thermo-mechanical analysis:

FINEL and DAMSWEL are both capable of analyzing 2-D geometrics with non-linear properties. The former has joint modeling incorporated.

Similar codes are available through the University of California at Berkeley, such as:

MIGRATE, which can be used for simplified 1-D finite differences analysis. As explained in a later section, certain modifications will make this code more useful.

HEAT, which can be used for 2-D finite element thermal-flow analysis. This program can be used together with programs SAP or NONSAP. These are 2-D or 3-D finite element codes are available for stress analysis of linear and non-linear systems, but not for modeling joints. Commercially available 3-D finite element codes, such as ADINA, CDC/ANSYS, or CDC/MARC, can be used to calculate directly the thermal stresses, allowing for non-linearities and some aspects of joint modeling.

STEALTH, which is commercially available and can perform highly non-linear analysis that considers thermomechanical coupling and that can allow thermal decrepitation of the basalt.

For the particular case when the plug is to be built with concrete, it will be interesting to study the temperatures caused by the heat generated in the plug during the hydrating process of the cement. Program DETECT (Polivika and Wilson, 1976) can perform a 2-D finite element linear analysis of the heat transfer process. The stresses can be computed by using ADINA, SAP, ANSYS, DAMSWEL, or any other similar finite element program.

(iii) Coupled Thermal-Fluid Flow Stress Analysis

In order to complement the results of thermal stress analyses, it is necessary to study the behavior of the plug under the combined thermal-fluid flow. The flow may be hot water, steam, or both. The analyses may be carried out with a few plug materials that presently seem most appropriate in view of the results of the thermal stress effects alone.

The method of analysis must allow for the same material characteristics as for the thermal stress analysis and must include the variation of permeability with stress. The computation loop must be carried out as shown in Figure 59. This computational process represents the link of several computer programs, an achievement that can be very time consuming. A link of this sort has already been developed; it involves the use of program GWTHERM to carry out the 2-D finite difference analysis of coupled thermal-fluid flow and program DAMSWEL to carry out the 2-D finite element stress analysis.

Similar capability could be achieved by linking locally available programs such as SHAFT79 or CCC for the 3-D finite difference analysis of the thermal-fluid flow and CDC/MARC or CDC/ANSYS for 3-D finite element stress computations. Program SAP could also be used to calculate the stresses, but this program lacks the joint elements. However, they may be used to compute the plug consolidation due to the seepage forces per unit volume.

Advantages in favor of SHAFT79 over GWTHERM are that the former considers 3-D geometry and allows for two-phase flow; however, it has the disadvantage of not allowing for temperature-

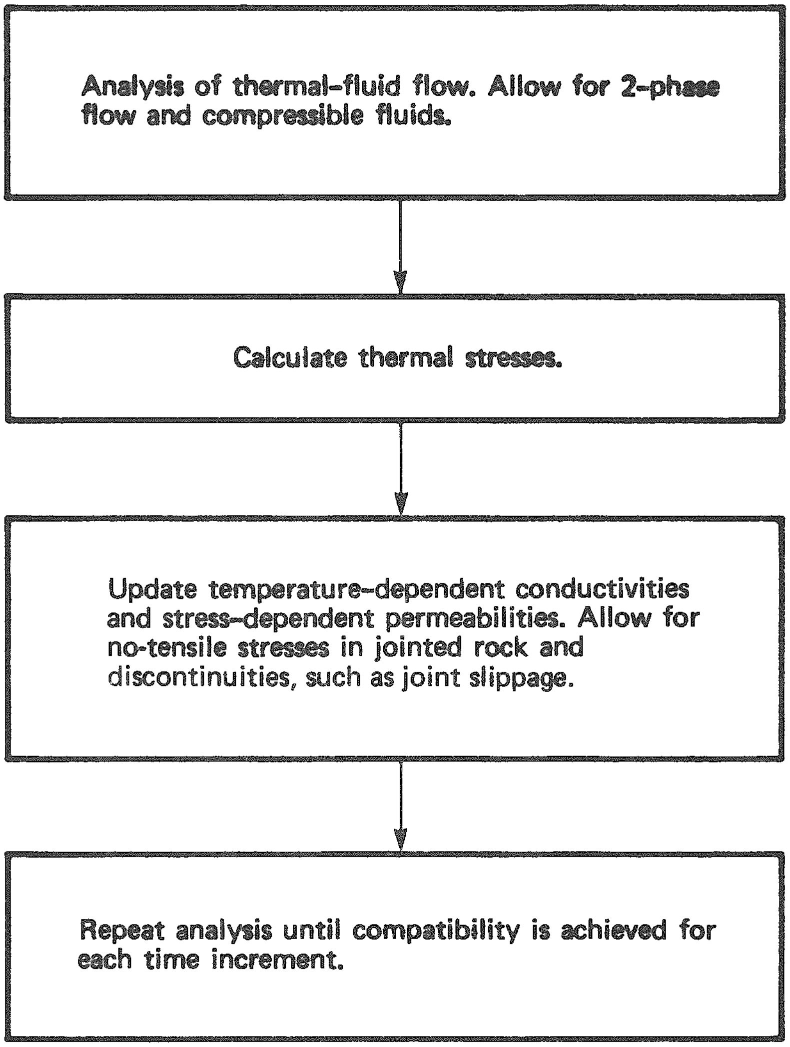


FIGURE 59

PROCEDURE FOR THERMAL-FLUID FLOW STRESS ANALYSIS dependent properties. On the other hand, program CCC allows for temperature- and pressure-dependent properties but is only valid for one-phase flow problems.

Because of practical considerations, it is advisable to use the GWTHERM-DAMSWEL link for coupled thermal-fluid flow analysis, using perhaps a combination of cross-sections and longitudinal sections of the tunnel-plug systems and making use of the set of plotting routines.

For a regional study of the influence of an aquifer in the long-term temperature distribution around the tunnel-plug system, program BASFEH may be used. This code performs a 2-D finite element analysis by using non-homogeneous, non-isotropic, temperature-dependent materials.

(iv) Fluid-Flow Stress Analysis

An important aspect of the plug behavior is the stability analysis under fluid flow, regardless of the temperature gradient. The problem is the effect of a large column of water equivalent to the full depth of the repository. The shear strength, s, at the joint plane and the plug/wall rock contact can be expressed as follows:

$$s = \bar{c} + (\alpha - u) \tan \Phi \quad (3.14)$$

where:
- c = cohesion
- α = total normal stresses
- u = pore water pressure
- Φ = friction angle.

The strength parameters c and Φ can be measured in the laboratory, whereas the total stresses and the pore water pressures must be calculated. For preliminary computation, a linear pore pressure distribution along the plug/wall rock contact and the factor of safety against slippage of the plug may be assumed; the factor of safety, which is assumed to be rigid, can be determined by using the equation shown above.

A better determination of the pore water pressures can be achieved by using programs SEEP or GWTHERM for a 2-D finite element analysis of the water flow. These pore pressures are to be incorporated in a stress analysis of the plug/wall rock system under the water head. We may use program FINEL, CDC/ANSYS, and CDC/MARC, which will account for the possible joint slippage, dilatancy, and other factors. Because the opening of joints may alter the flow significantly, this type of analysis may have to be performed in an iterative fashion to follow a progressive type of failure step by step. Perhaps a program link of the type used for the coupled thermal-fluid flow is necessary. Any of the codes used for stress analysis can compute the plug consolidation due to seepage forces per unit volume.

Description of Suggested Computer Codes

The phenomena that could be important to the design of the plugging system may include analyses such as: ground-water flow, thermally induced stress, phase change in ground water, dynamic effect from blasting, seismic events, temperature-dependent rock properties, coupling of thermal stress and ground-water flow, non-linear behavior along joints, and radiation effect on rock and on rock properties. No single analysis or modeling technique is able to provide solutions to all these problems. This section presents, however, a brief description of the computer programs selected for further assessment as to possible use and of some guidelines for the selection of other codes if necessary.

A comprehensive compilation of the available computer codes is presented in Table II. There is a large number of codes, some of which are complex, general purpose programs that become cumbersome and expensive to run for simple problems. Therefore, it may be more convenient to work with less general but more applicable programs that have been developed for a particular problem. Because of the time constraint in the preparation of this report, many details relative to the use of the computer programs are not known, and recommendations for their use have been made on the general applicability of their modeling method.

Useful results can be obtained by assuming as a first approximation that the fluid and heat flow processes are uncoupled and by solving simple cases; then a more detailed solution may be obtained.

For the solution of thermomechanical problems, the following codes may be used:

SALT2: A closed-form 2-D solution for heat flow analysis (University of Minnesota).

SALT3: Uses the displacement discontinuity and performs 2-D solutions based on an exponentially decaying line heat source (University of Minnesota).

TABLE II
SUMMARY OF COMPUTER CODES DISCUSSED[a]

Basis of Method	Code Name	Reference	Source of Code	Capabilities	Comment
Closed Form	UM3DH	Hardy and Hocking (1978)	UM[b]		
	SALTZ	"	UM[b]		
	FILINE	"	LBL[c]		
Integral Method	SALT	"	OWI[d]		
	SALT2	"	UM[b]		
	BASUM	"	UM[b]		
	EXPAR	"	UM[b]		
	REPOS	"	UM[b]		
	BEH2D	"	Dames & Moore		
	DAMBIT	"	Dames & Moore		
Finite Element	FINEL	"	Dames & Moore/ Imperial College		
	DAMSWEL	"	Dames & Moore/ Swansea University		
	BASFEH	"	UM[b]		
	SAP	"	UCB[e]		
	NONSAP	"	UCB[e]		
	RSI/TRANCO	Callahan and Fossum (1977); Parisean (1975)	RE/SPEC		
	CDC/ANSYS		Swanson Analysis System		
	CDC/MARC	Ayres (1973)	Marc Analysis Research		
	DIFFUS2	Hardy and Hocking (1978)	UM[b]		1-D Regional
	HEAT	Taylor (1975)	UCB[e]		
	DOT	Polivika and Wilson (1976)	UCB[e]		
	DETECT	"	UCB[e]		
	ADINA	Bathe (1975)	MIT[f]		
Finite Difference	KO/TEMP	Wilkins and others (1975)	LLL[g]		
	WONDY/ TOODY	Hardy and Hocking (1978	Sandia Industries		
	PISCES	"	Physics International		
	STEALTH	Hoffman (1976)	Science Applications		
	GWTHERM	Hardy and Hocking (1978	Dames & Moore		
	MIGRATE	Abdel-Hadi (1978)	UCB[e]		1-D
	SHAFT79	Pruess and others (1979)	LBL[e]		
	CCC	Lippmann and others (1977)	LBL[e]		1-D Reservoir Regions

[a]After Rahman and Kao (1979)

[b]University of Minnesota

[c]Lawrence Berkeley Laboratory

[d]Office of Waste Isolation

[e]University of California at Berkeley

[f]Massachusetts Institute of Technology

[g]Lawrence Livermore Laboratory

DAMSWEL: Performs finite element, 2-D thermoelastic solutions, and handles non-linear and temperature dependent properties. It is a large code and requires experienced operation. Adequate for very detailed analysis (Dames & Moore and Swansea University)

FINEL: Large commercial program can perform 2-D finite element analyses incorporating non-linear material characteristics as well as joint and crack discontinuity formulations in the computation of stresses. This code also has flexible output options (Dames & Moore and Imperial College).

HEAT: Small 2-D finite element code for heat conduction; for stress computation, needs to be linked with SAP, NONSAP, or equivalent programs (University of California - Berkeley).

DETECT: Small 2-D finite element code for linear analysis of temperature buildup during the different stages of construction of concrete structures. Does not compute stresses (University of California - Berkeley).

BASFEH: A 2-D finite element analysis of heat conduction. Accepts inhomogeneous, anisotropic, temperature-dependent materials. This program presents an aquifer element to model heat transfer due to forced connection via ground-water flow. This feature is useful for regional studies. (University of Minnesota).

The following are some candidate codes for coupled thermo-fluid flow analysis:

MIGRATE: Small 1-D finite code for moisture migration under thermal gradient. This code could be modified to account for water pressure head and to allow for temperatures above 100°C, and thus would become much more useful. Does not compute stresses (University of California - Berkeley).

SHAFT 79: A 3-D finite difference program to analyze the coupled mass energy transport for two-phase flow in porous media. Rock properties are independent of temperature or pressure. Does not compute stresses but may be used for vapor-fluid thermal-flow (Lawrence Berkeley Laboratory).

CCC: A 3-D finite difference program to analyze the one-phase coupled thermal-water flow in heterogeneous isotropic media in a local or regional geometry. The solid and fluid properties are temperature- and pressure-dependent. The 1-D consolidation of saturated media is taken into account. This program can be linked to SAP, ADINA, or the equivalent for computation of stresses (Lawrence Berkeley Laboratory).

GWTHERM: A 2-D finite difference code for coupled thermal-fluid flow analysis. Allows for anisotropy and temperature-dependent hydrologic properties. This program has been linked with program DAMSWEL using other auxiliary codes for stress computation and updating of porosities and permeabilities as function of stresses. This package also allows the computation and plotting of positions of particles released at various elapsed times and offers flexible output options of material properties, calculated pressure, temperature, and velocity values during the computational process. It seems quite a thorough package and is highly recommended (Dames & Moore).

Some computer programs for calculation of stresses are:

SAP: A 3-D general purpose finite element code for static and dynamic analysis of linear systems. The program may accept temperature gradients for thermal stress computations (University of California - Berkeley).

NONSAP: A 3-D general purpose finite element code for non-linear analysis. This program will accept orthotropic and isotropic elements and a diversity of curve descriptions, including tension cutoff, and will analyze problems with large displacement, large strains, or other non-linear material properties. This code is very appropriate for modeling behavior around underground excavations. It is possible to add 2-D or 3-D joint elements (University of California - Berkeley).

CDC/ANSYS: A 3-D general purpose finite element code for thermal stress calculations. This program models joint features and non-linear material properties. It is expensive to run and the plotting subroutines are not implemented (Swanson Analysis System).

CDC/MARC: A 3-D general purpose finite element code for thermal stress calculations. This code also uses joint modeling and non-linear material properties but is expensive and cumbersome to run. This program presents a good post-processing for plotting and data output (Marc Analysis Research).

STEALTH: A 3-D commercially available finite difference code for non-linear, coupled thermal-fluid flow stress computation. This program can accept many different kinds of models, such as strain-dependent conductivity, to model the thermal basalt decrepitation. Errors were detected in the axisymmetric solution (Science Applications).

ADINA: A 3-D commercially available, general purpose program for non-linear, thermal stress computation (Massachusetts Institute of Technology).

Computer program suggested for the determination of seepage pore water pressures:

SEEP: A 2-D finite element analysis for steady state water flow in porous media (University of California - Berkeley).

Conclusion

For initial studies, it seems convenient to obtain only the GWTHERM-DAMSWEL package, and perhaps the BASFEH, to perform most of the required analysis. Adequate treatment of random joints will require a great deal more computational effort and extensive laboratory testing.

3.1.3 Probabilistic Analysis of Thermal Stresses and Seepage

Following the work described in Section 3.1.2.1, Preliminary Analysis, it was decided to concentrate the probabilistic analysis on two problems: the stress increase along the wall of a plugged tunnel due to temperature increases, and the flow rate of water through a plug and its surroundings due to hydrostatic pressure in the repository. The following subsections describe the analysis of these two problems in detail.

3.1.3.1 Discussion of Steps of Methodology

(i) Bounding the Problem

The complete analysis of the potential for leakage of radionuclide into the biosphere requires simultaneous examination of all system plugs in a conceptual design, as well as all types of failure modes, over time. It was decided to examine only one plug location and only certain designs and failure modes. The bounded problem was as follows:

Plug Location: Class I plug located in a horizontal tunnel connecting the main repository to the main shaft.

Plug Design:

- Compacted clay or concrete;
- Homogeneous with flat plug ends;
- No multiple material designs;
- No plug lining; or
- Designs without cutoffs.

Failure Modes:

- Leakage due to slow permeation through plug and disturbed basalt; or
- Failure due to thermal expansion and contraction.

Additional boundary conditions were specified when ambiguities or design alternatives made it difficult to calculate or specify the values of certain design parameters.

(ii) Assess Ranges in Modeling Parameters

The main difference between the numerical and probabilistic studies is the emphasis on ranges of uncertainty in the modeling parameters. Where a typical engineering analysis might use "most likely" or average values as the input parameters to obtain a single estimated value, a probabilistic analysis attempts to find complete probability distributions over the ranges of the input parameters. These distributions can then be systematically combined using the laws of probability to obtain a distribution over the quantity of interest.

In general, there are three basic ways that a probability distribution can be obtained on a variable: (1) by repeated trials or samples; (2) by the use of a known probability distribution (e.g., normal); or (3) by the use of expert judgment. For example, suppose the permeablility of basalt (K_b) is the parameter of interest. One way to find the probability distribution on K_b is to run a large number of tests calculating K_b for many basalt samples. Statistics can be kept on the range of K_b observed and a probability distribution inferred. Or experiments with other types of rock may have indicated that rock permeabilities are normally distributed with means and variance related to known parameters. In this case, it may be reasonable to assume that permeability of basalt will also be normally distributed.

If no standard (e.g., normal, chi-squared, etc.) distribution seems reasonable, and it is not possible to do repeated tests, the best procedure is likely to be the direct encoding of an expert's judgment. The usual procedure is through an interview process where the assessor offers the expert a series of choices about the relative likelihoods of two uncertain events. These might be choices about two ranges of the variable of interest (e.g., "Is the permeability most likely to be above or below 10^{-8} cm/sec at a depth of 0.4D?"), or choices comparing a known probability with the quantity of interest (e.g., "Which is more likely: throwing three heads in a row with a fair coin or observing a permeability greater than 10^{-3} cm/sec at a depth of 0.1D?"). By careful use of these types of interview techniques and consistency checks, a reasonably accurate representation of the expert's judgment of the probability distribution can be obtained.

(iii) Establish Probability Distributions for Design Criteria Parameters

Once probability distributions have been obtained over those modeling parameters with the greatest influence on the design criteria, deterministic models, such as Darcy's Law for flow through porous media, can be used to establish a distribution over the design criteria. This is a relatively straightforward process that can be accomplished using simple computer simulation techniques or by decision techniques using discretized versions of the probability distributions.

3.1.3.2 Thermal Stresses in Plug

The engineering analysis given in Appendix B resulted in the following equation for stress increase:

$$p = \frac{TE_p E_R[a_R (1+\nu_R) + a_p (1+\nu_p)(1-2\nu_R)]}{(1-2\nu_R)[E_R(1+\nu_p)(1-2\nu_p) + E_p(1+\nu_R)]} \qquad (3.15)$$

where:

p = stress increase at interior wall of opening
T = temperature
a_p = plug thermal expansion coefficient
a_R = rock thermal expansion coefficient

ν_p = plug Poisson's ratio
ν_R = rock Poisson's ratio
E_p = plug Young's modulus
E_R = rock Young's modulus.

Some of these variables are either partially or completely under the control of the plug designers. Other variables are properties of the rock surrounding the repository and cannot be estimated exactly until the repository site is determined. For this preliminary probabilistic analysis, it was assumed that the plug material parameters were known exactly and corresponded to the values given earlier in "Thermomechanical Stresses in Hard Plugs." The rock properties were assumed to have ranges and most likely values corresponding to those given in Appendix A. The values used for the modeling parameters are:

Variable	Most Likely Value (Mode)	Range
T	50°C	Design parameter
α_p	10^{-5}/°C	Design parameter
α_R	6.2 x 10^{-6}/°C	(2.9 to 11.6) x 10^{-6}/°C
ν_p	0.20	Design parameter
ν_R	0.25	0.05 to 0.31
E_p	30 GPa	Design parameter
E_R	77 GPa	63.1 to 85.6 GPa

The next step was to convert the range and most likely values for the three uncertain quantities (a_p, ν_R, and ε_R) into probability distributions. The end percentage point on the ranges were assumed to represent the 5 percent and 95 percent percentiles of the probability distributions (meaning that 90 percent of the observations could be expected to fall within the given range). To obtain a complete probability distribution over these quantities, it was decided to fit the values to one of the standard probability distributions (e.g., normal, chi-squared). Most of these distributions require knowledge of the mean, median, or standard deviation of the data to allow a fit to be made. To estimate the means, medians, and standard deviations for the distributions, the following empirical formulae were used (see Perry and Greig, 1975):

$$\mu = \text{mean} = (P_5 + 0.95\ M + P_{95}) \tag{3.16}$$

$$P_{50} = \text{median} = 1.59\ (\mu) - 0.293\ (P_5 + P_{95}) \tag{3.17}$$

$$\sigma = \text{standard deviation} = (P_{95} - P_5) \tag{3.18}$$

where:

M = mode; and

P_n = the n^{th} percentile of the distribution [i.e., Prob $(P < P_n) = n\%$].

Because the mode for each of the three variables to be fit was not equal to its midpoint of the range, the normal (bell shaped) distribution was not appropriate, and non-symmetric probability distributions were indicated. To allow random samples to be made, it was necessary to approximate the distributions. The lognormal probability distribution, which has the appropriate non-symmetric shape, is reasonably tractable computationally and was used to fit each of the three parameters.

The lognormal distribution is characterized by two parameters; the median (P_{50}) and the shape parameter (S). The median could be computed from Equation 3.17 above, while S could be computed from the formula (Hastings and Peacock, 1975):

$$S = SQRT\ [Ln\ (P_{50}/mode)] \qquad (3.19)$$

The variables ν_R and E_R were both skewed in the direction opposite that of the lognormal distribution. In these cases, a lognormal distribution was fit to the quantity (MAX-X), where MAX was an assumed maximum value for the variable. For E_R this value was assumed to be 100 GPa. For ν_R it was possible to compute this value by using the three known quantities: mean, median, and mode in three equations to solve simultaneously for the median, S, and MAX. Subtracting the resulting lognormal distribution from MAX yields the desired distribution over ν_R or E_R. The resulting probability distributions were:

$$\begin{aligned} a_R &\sim \text{Lognormal (median = 6.72, S = 0.283)} \\ \nu_R &\sim 0.333 - \text{Lognormal (117, 0.585)} \qquad (3.19) \\ E_R &\sim 100 - \text{Lognormal (24, 0.206).} \end{aligned}$$

To get an idea of the effect of these distributions on the quantity of interest, P_M (stress increase), a simple computer model was implemented. This model used a random number generator to sample values for α_R, ν_R, and E_R from the appropriate probability distributions. These values were then plugged into Equation 3.15 along with the constant quantities, and a value for P was computed. For α_R, ν_R, and E_R, 100 values were then sorted from lowest to highest to give an approximation to the cumulative probability distribution function over P, implied by Equation 3.15 and the other assumptions made. This distribution is shown in Figure 60. The results indicate a 5 percent chance that P will be less than (or equal to) 15 MPa, a 50 percent chance that $P < 22.2$ MPa, an 80 percent chance that $P \leq 28$ MPa (the "nominal" value), and a 95 percent chance that $P \leq 37.5$ MPa (compared with 34.2 MPa given in "Thermal Stresses in a Confined Elastic Plug and Its Environment" and 30 MPa for the assumed elastic limit of concrete).

3.1.3.3 Flow Through Plug

Flow through the plug consists of flow through the plug itself and flow through the disturbed basalt surrounding the plug. The basic formula used in the analysis is Darcy's law:

$$Q = Kia \tag{3.20}$$

where:

Q = Quantity of flow

K = Permeability

i = $\Delta H/L$

ΔH = Difference in hydraulic head between plug ends

L = Length of plug

a = Cross-sectional area.

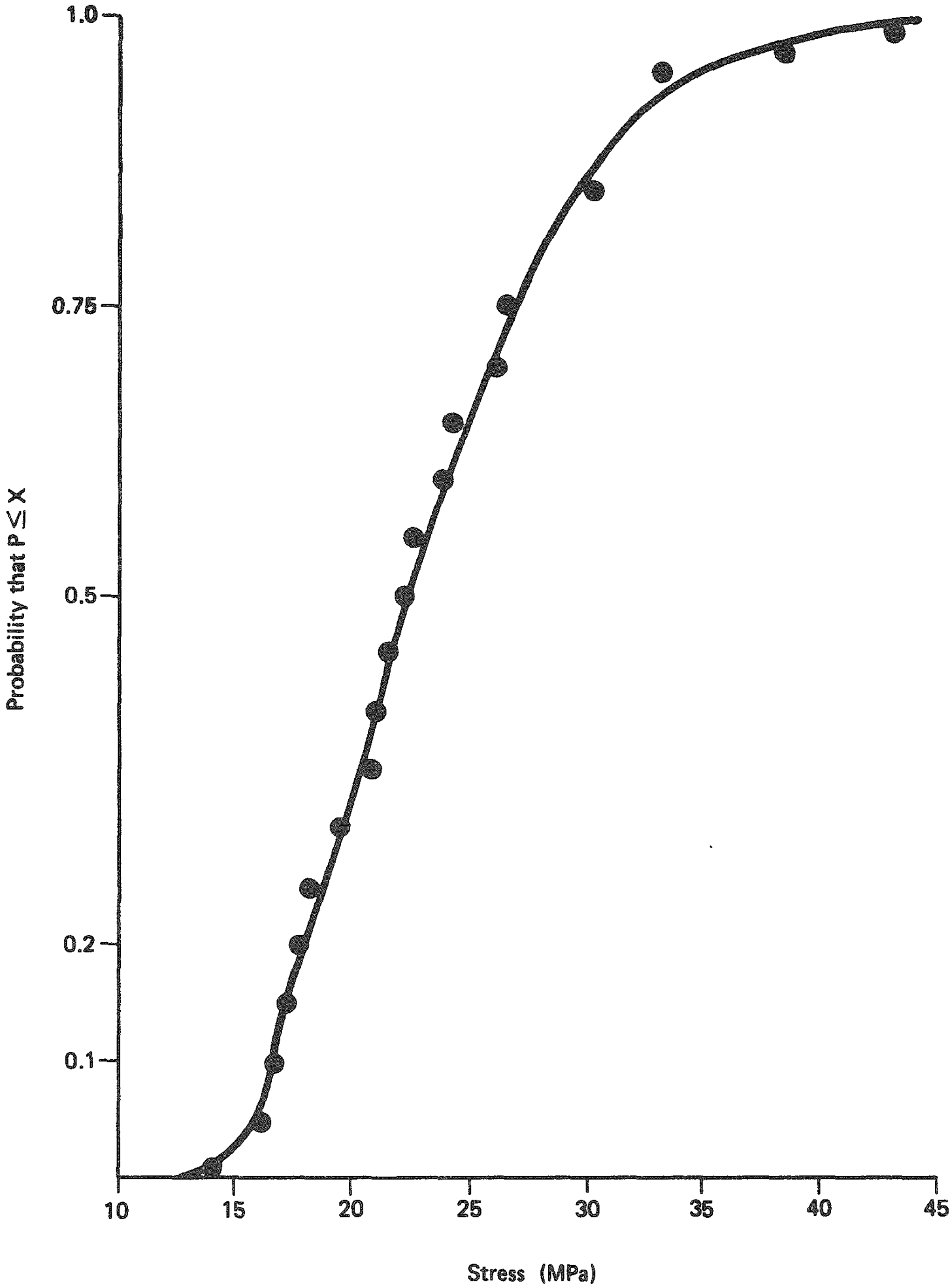


FIGURE 60

CHANGE IN THERMAL STRESS AT INTERIOR OF PLUG OPENING

The question asked in this section was: What length plug will be needed to limit the flow to 1 m^3/year? To answer this question, Equation 3.20 is rearranged to:

$$L = K(\Delta H/Q)a. \qquad (3.21)$$

For the purposes of this analysis, it is assumed that the following values are known:

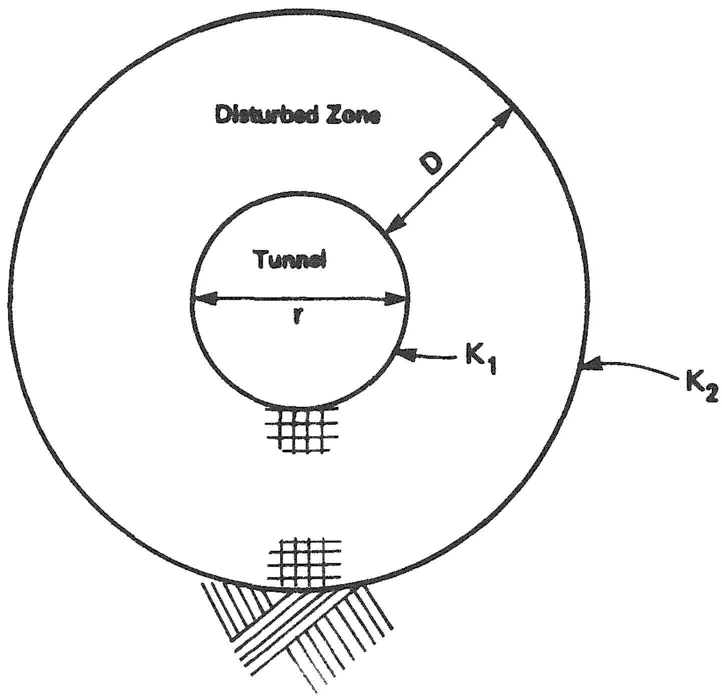
$$Q = 1\ m^3/\text{year}$$
$$\Delta H = 160\ m$$
$$a = \pi(3.5\ m)2 = 38.5\ m^2.$$

In addition, it is assumed that the plug material can be designed and installed to achieve a permeability of 10^{-9} cm/sec, so that the plug length needed to limit the flow to 1 m^3/yr is:

$$L = (10^{-9}\ \text{cm/sec}) \times \frac{(160\ m)}{1m^3/yr} \times (38.5\ m^2) \times \left[60^2 \times 24 \times 365.25\right] \frac{sec}{yr} \times \frac{0.01m}{cm}.$$

Calculating the flow through the disturbed area is a much more difficult problem, complicated by the lack of information on this subject. Conceptually, the disturbed area can be seen as an area of increased permeability, with the maximum permeability occurring at the tunnel edge and permeability gradually decreasing away from the tunnel until it is equal to that of undisturbed basalt. Figure 61 shows the parameters associated with the disturbed area.

For modeling purposes, it was assumed that permeability decreased exponentially as distance from the tunnel surface



EXPLANATION

r	Diameter of tunnel = 7 m
D	Distance to reduce permeability to that of undisturbed basalt
K_1	Permeability at tunnel edge
K_2	Permeability of undisturbed basalt

FIGURE 61

PARAMETERS OF DISTURBED ZONE

increased; that is, the permeability at a point X in the interior of the disturbed zone K(X) is given by:

$$10^{\left\{\text{Log } K + \left[\left(\text{Log } \frac{K_2}{K_1}\right)\left(\frac{X-r}{D}\right)\right]\right\}} \qquad (3.22)$$

This linear function in the log of K was designed so that:

$$K\ (r) = K_1$$
$$K(D + r) = K2$$

To find the total flow through the disturbed area, calculus must be used to integrate Kia across the disturbed zone. The formula used was:

$$Q = \int_{r}^{r+D} K(X)\, i2\pi X dX \qquad (3.23)$$

where K(X) was defined in Equation 3.22.

Solving this definite integral yields:

$$Q = \frac{2\pi i K_2 D^2}{L_n(K_2/K_1)} \left\{\left(1-\frac{K_1}{K_2}\right)\left[\frac{r}{D} + L_n\left(\frac{K_2}{K_1}\right)^{-1} + 1\right]\right\} \qquad (3.24)$$

Solving this for the length of plug required

$$\left(L = \frac{H}{i}\right) \qquad (3.25)$$

and substituting the known values r = 3.5 m, H = 160 m, Q = 1 m^3/yr, and $K2 = 10^{-9}$ cm/sec yields:

$$L = \frac{0.316D^2}{-20.72-L_nK_1}\left\{\left(1-K_1 \times 10^9\right)\left[\frac{7}{D} + \left(L_nK_1 - 20.72\right)-1\right]+1\right\} \qquad (3.26)$$

This equation reduces L to a function of the unknown quantities D and K_1.

To identify ranges of values for D and K_1, judgmental probability distributions were assessed using standard techniques (Spetzler and Stael von Holstein, 1972) to encode an in-house expert's judgment. The resulting cumulative probability distributions are shown in Figures 62 and 63. Due to the difficulty of specifying permeability to more than the nearest half-order of magnitude, it was decided to define this distribution for the density function shown in Figure 64. During the assessment of D, the value of D was stated as dependent on the value of K_1 observed. The distribution shown in Figure 63 was assessed using a nominal value of $K_1 = 10^{-6}$ cm/sec. By definition, when $K_1 = 10^{-9}$ cm/sec, then $D = 0$. It was assumed that for K_1 in the range $10^{-9} < K < 10^{-3.5}$, a reasonable approximation was that the median (D_{50}) of D varied linearly with the log of K_1:

$$D_{50}(K_1) = 2.333 \text{ Log } K_1 + 21 \qquad (3.27)$$

which was calculated to insure that

$$D_{50}(10^{-9}) = 0 \text{ and } D_{50}(10^{-6}) = 7 \text{ m.}$$

It was assumed that the 5th percentile would remain constant at $D_{05} = 152$ m. [Here, D_n is the number such that Prob $(D \leq D_n) = n\%$.]

The shape of the distribution for D suggested that the extreme value distribution would fit the assessed values for Ln(D). This distribution is characterized by parameters a and b, which can be found by solving the following simultaneous equations:

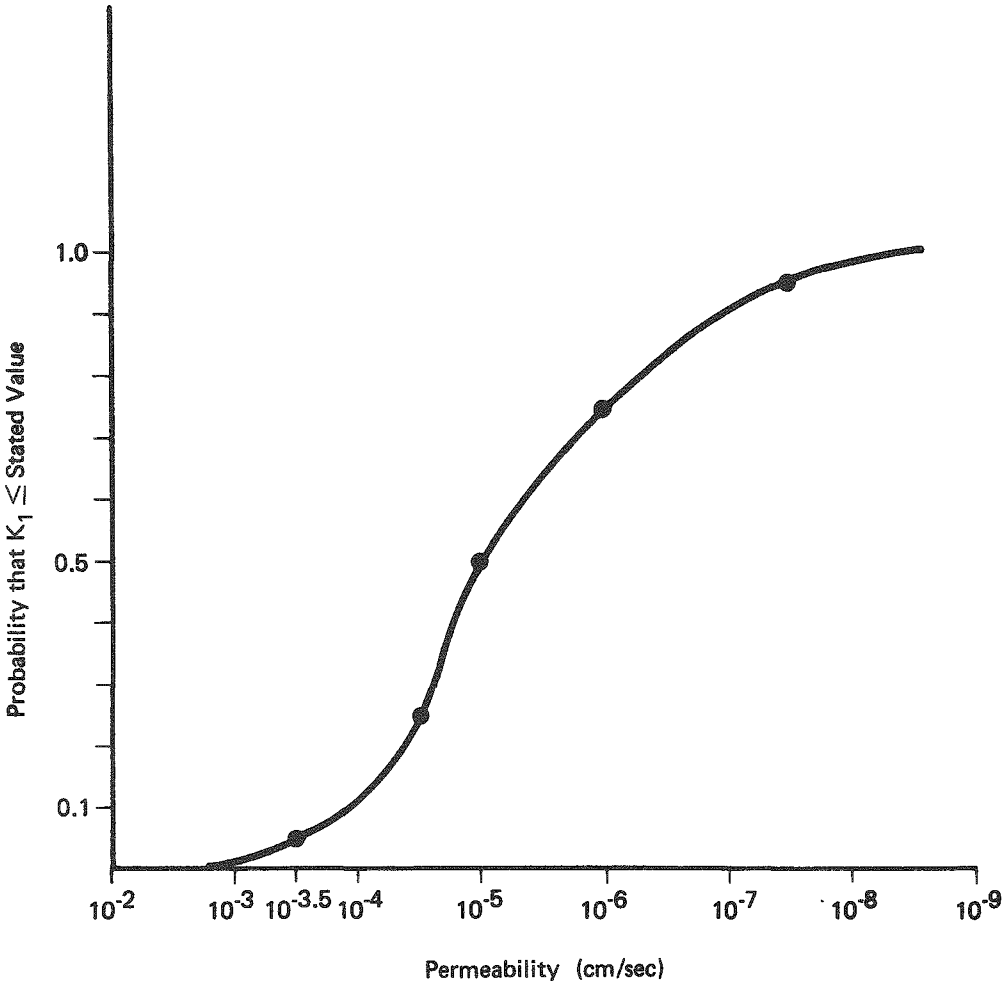
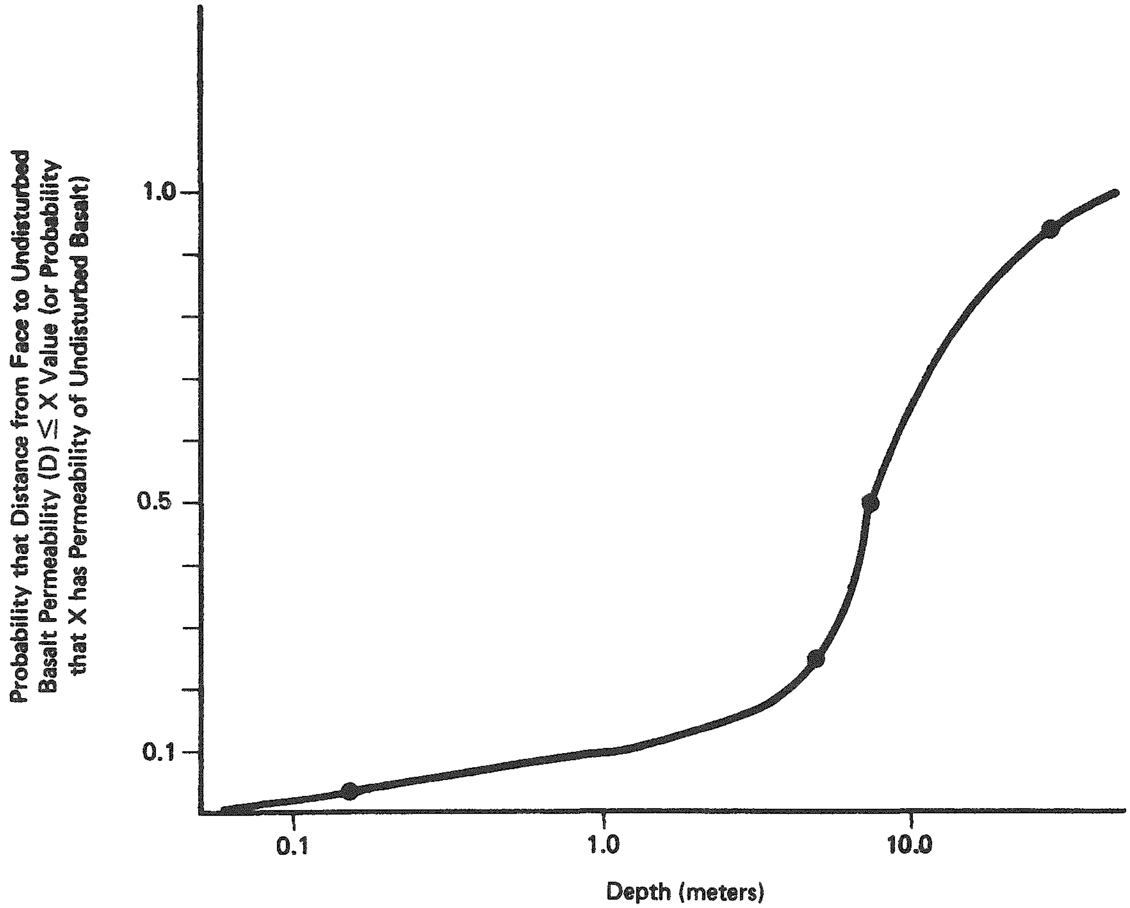


FIGURE 62

PERMEABILITY AT TUNNEL FACE (K_1), ASSUMING PERMEABILITY OF UNDISTURBED BASALT IS 10^{-9} CM/SEC



NOTE: Distance from tunnel wall to 10^{-9} cm/sec permeability (D), assuming permeabilities of 10^{-6} cm/sec at tunnel face and 10^{-9} cm/sec for undisturbed basalt.

FIGURE 63

DEPTH OF DISTURBED ROCK ZONE IN TUNNELS (PROBABILITY)

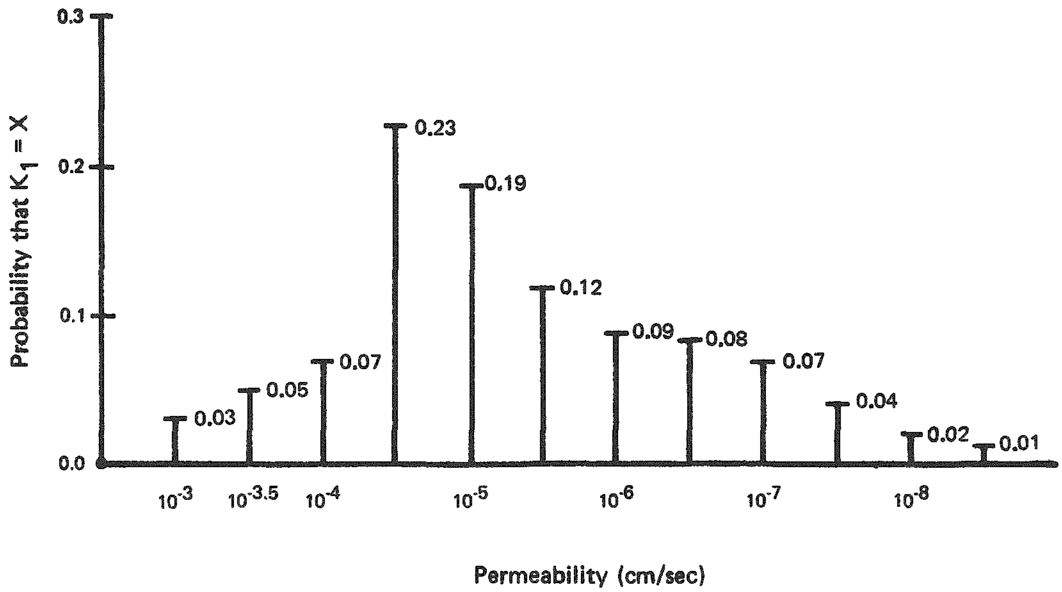


FIGURE 64

DISCRETIZED PROBABILITY DENSITY FUNCTION FOR PERMEABILITY AT TUNNEL FACE (K_1)

$$\mathrm{Ln}\ (D_{05}) = a + 1.05b \tag{3.28}$$

$$\mathrm{Ln}\ [D_{50}\ (K_1)\ ] = a + 0.367b \tag{3.29}$$

These equations were obtained by substituting values from Equation 3.27 into the general inverse distribution function for the extreme value distributions:

$$D_n = a + b\ \mathrm{Ln}\ [1/(1-n/100)] \tag{3.30}$$

It was found that using $D_{05} = 0.152$ and $D_{50}(10^{-6}) = 7$, the values assessed and shown in Figure 63 resulted in a very poor fit to the observed data. However, adjusting to $D_{05} = 0.46$ m resulted in an extremely good fit to all points except $D_{25} = 4.9$ m (which had a computed value of $D_{25} = 2.8$ m). It was felt that the assessed value of D_{25} may have represented an example of "anchoring" to the median value of 7 m and that reassessment of this point would bring it closer to the computed value. It was felt that the assessed D_{05} point may have represented a more extreme point in the distribution. The assessed D_{05} equals the computed D_{02} and, because this is a difficult region for assessing points, it was decided that the fitted distribution was reasonable for purposes of this analysis. In Figure 65, the assessed and fitted distributions for $K_1 = 10^{-6}$ cm/sec is compared.

To compute a distribution over L, a Monte Carlo approach was used. First K_1 was generated using a random sample from the density function of Figure 64. This number was used as input to Equation 3.29 to allow calculation of the parameters a and b of the Extreme Value distribution (D_{05} was considered to be fixed at 0.46 m). The value of D was then generated as a random sample from this distribution. The values for K and D

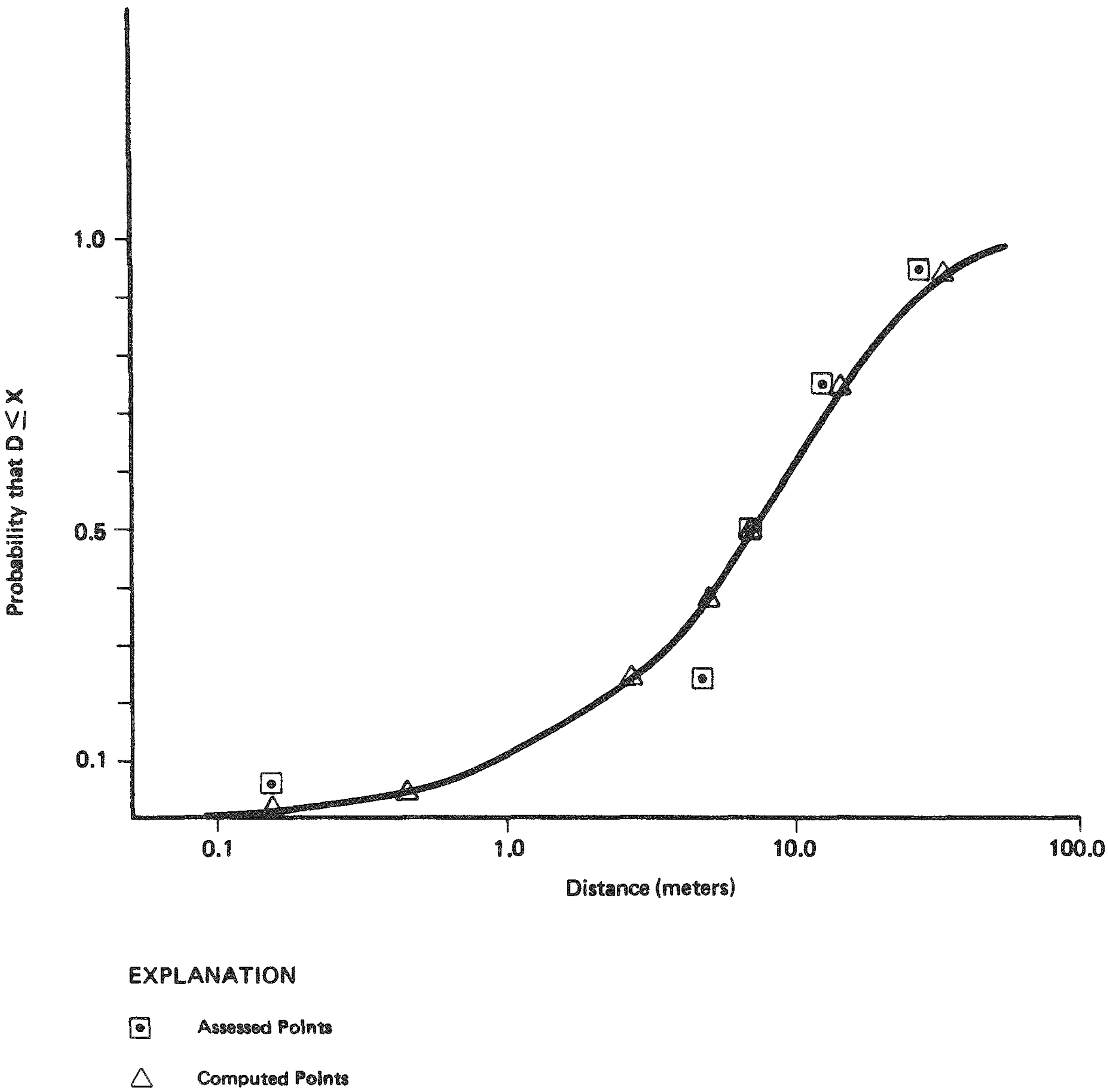


FIGURE 65

COMPARISON OF COMPUTED AND ASSESSED DISTRIBUTION FOR DISTANCE FROM TUNNEL FACE (WHERE K = 10^{-6} CM/SEC) TO 10^{-9} CM/SEC IN-SITU PERMEABILITY (D) were then used in Equation 3.26 to give a value for L. The process was repeated 100 times to give a range of values for L. These values are presented in a cumulative summary in Figure 66.

The extreme range of values shown on Figure 66 is disconcerting. It was felt that the assumptions relating D to K_1 may have been unreasonable in that large values of K_1 resulted in a large median value for D; therefore, a run was made using the assumption D_{50} (K_1) = 7 m for all K_1 in Equation 3.29. This resulted in the distribution shown in Figure 67. This also shows an extremely wide range.

One possibility for reducing permeability is the use of grouting. As discussed earlier, grouting might reduce the maximum permeability to about 10^{-6} cm/sec. Two runs were made to examine the effects of grouting. The first run assumed that values of K_1 were chosen as before and used to compute a median value for D from Equations 3.20 and 3.29. The value for D was then sampled as before, and if K_1 was greater than 10^{-6}, it was revalued to that figure. The new sample values for D and K_1 were then used in Equation 3.26 as before. The second run assumed a median for D of 7 m. These runs resulted in values for L that were more reasonable, although the higher values were still very large. These results are shown in Figures 68 and 69.

Two conclusions can be made from these preliminary results. First, the wide ranges shown for the required length of plug indicate that much more work needs to be done on the question of flow through the disturbed area. Second, because the probability distribution on permeability was assessed on the basis of predicted smooth borehole blasting performance, it

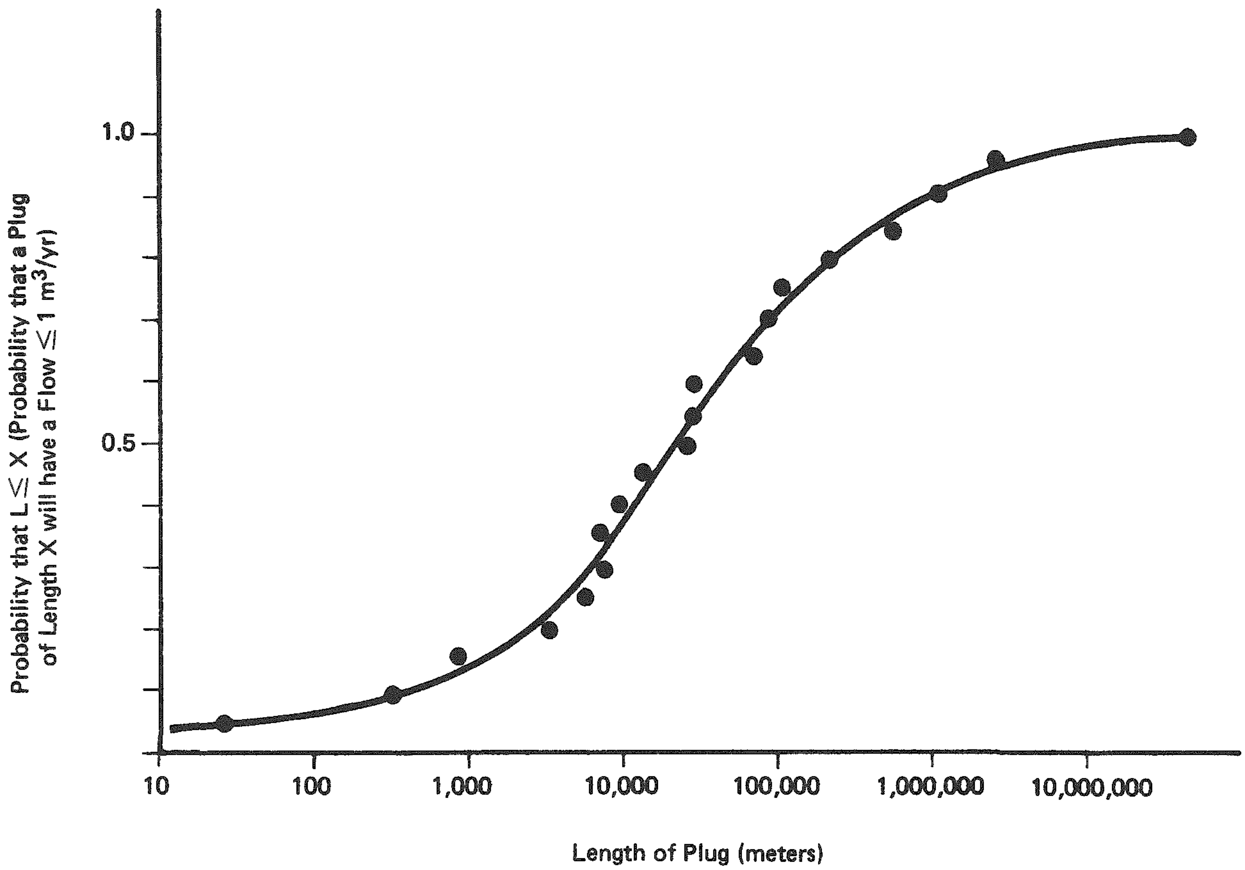


FIGURE 66

LENGTH OF PLUG NEEDED TO ASSURE FLOW OF 1 M^3 /YR;
CASE I: NO GROUTING, D_{50} = F (K_1)

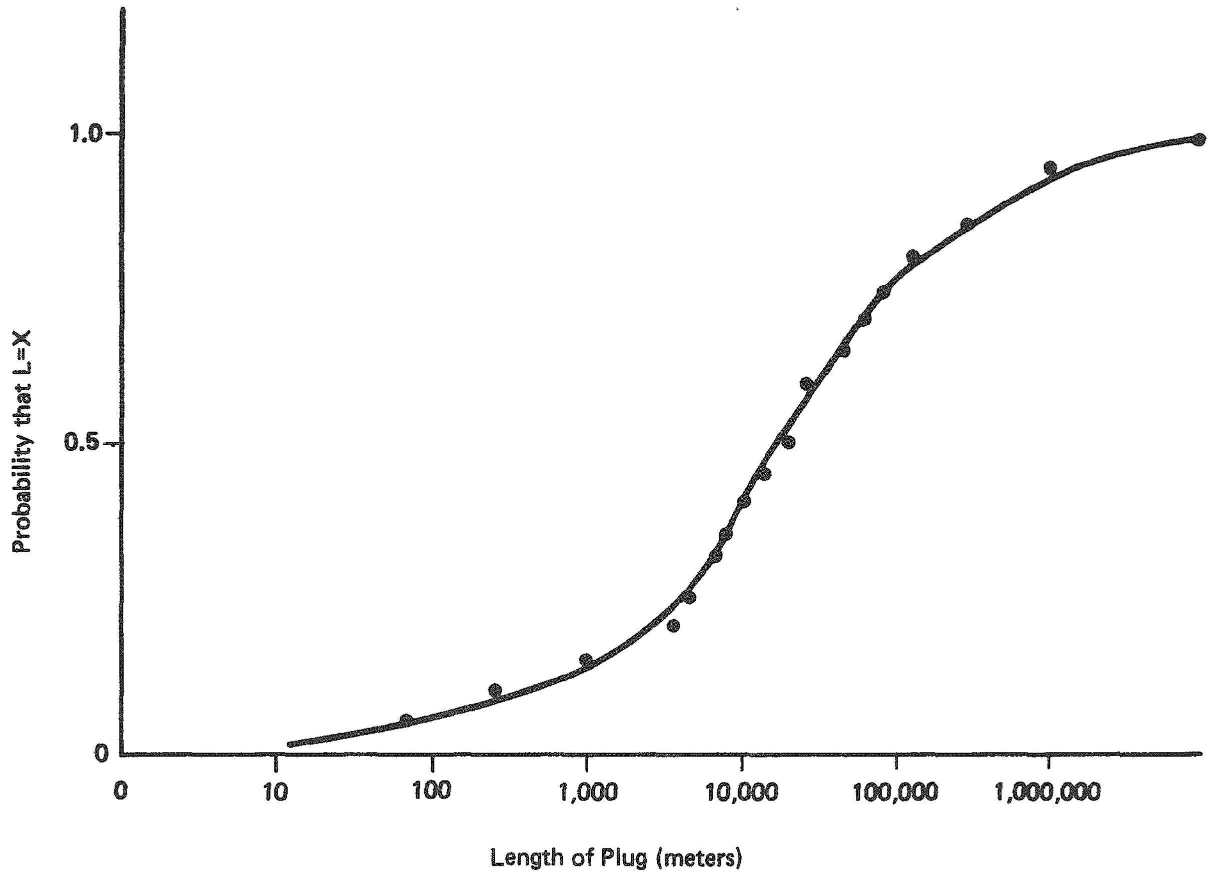


FIGURE 67

LENGTH OF PLUG NEEDED TO ASSURE FLOW OF 1 M^3/YR;
CASE II: NO GROUTING, D_{50} = CONSTANT

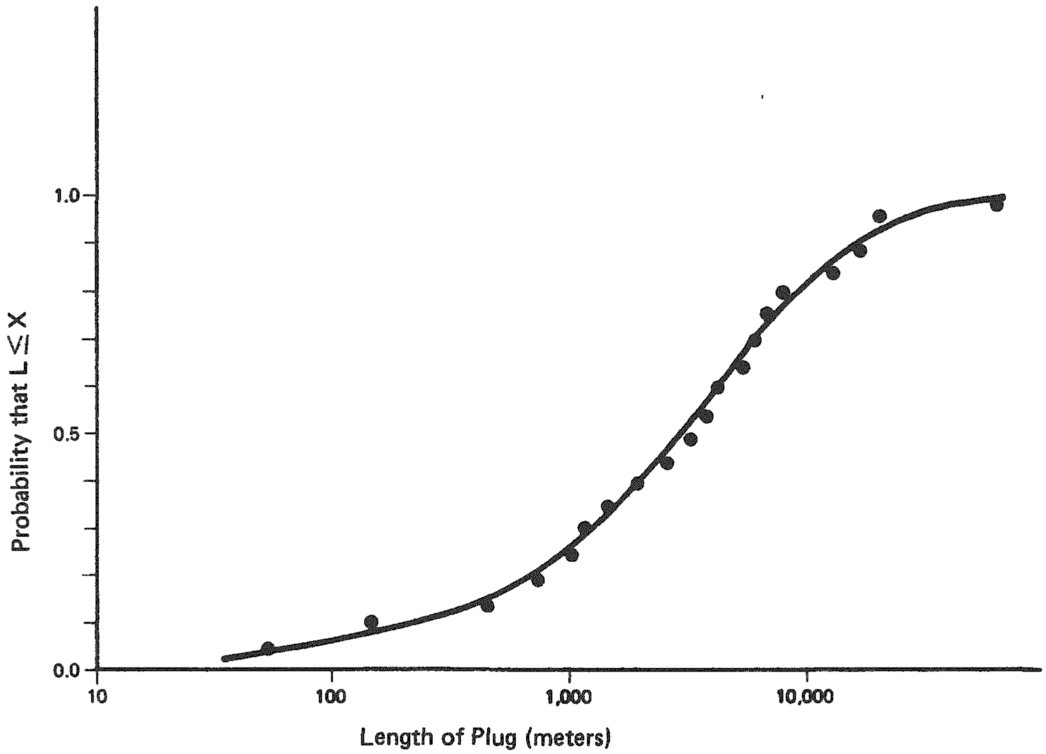


FIGURE 68

LENGTH OF PLUG NEEDED TO ASSURE FLOW OF 1 M^3/YR; CASE III: GROUTING TO ASSURE MAXIMUM PERMEABILITY OF 10^{-6} CM/SEC, D_{50} = CONSTANT

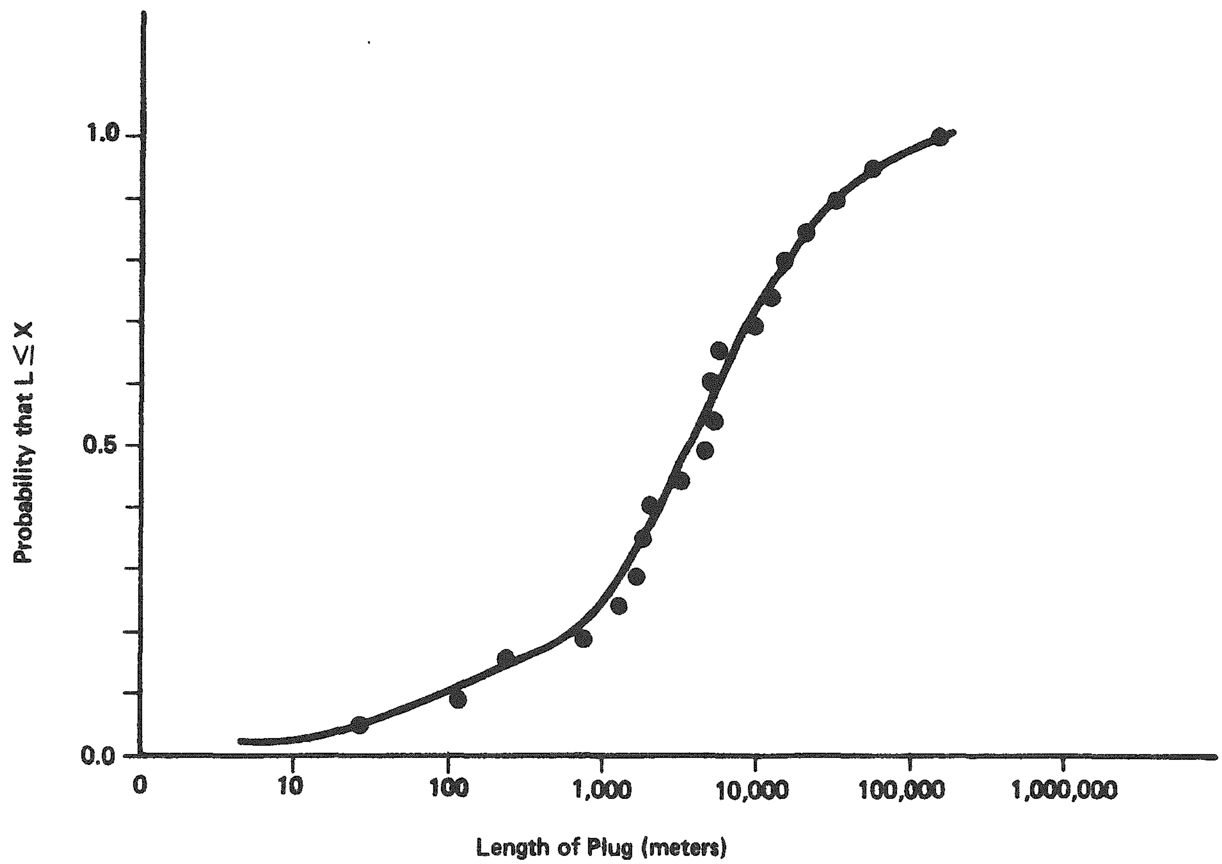


FIGURE 69

LENGTH OF PLUG NEEDED TO ASSURE FLOW OF 1 M^3/YR;
CASE IV: GROUTING, $D_{50} = F(K_1)$

appears that this method of construction may cause excessive permeability problems. If blasting is used, grouting or other methods to reduce permeability changes may be necessary. Another possibility is to use "cutoffs," which essentially replace a portion of the disturbed area with plug material. Although this was not analyzed formally at this point, the preliminary results on the length of the plug needed to reduce flow to 1 m^3/yr indicate that replacing even a small portion of the disturbed area with cutoffs could substantially reduce required plug length.

3.1.4 Numerical Analysis of Radionuclide Barrier Performance of Plugs

The purpose of this part of numerical analysis was to estimate the minimum length of plug required so that the maximum credible concentration of one specific radionuclide at the end of the plug will be below the maximum allowable concentration stipulated by NRC Draft Regulation 10 CFR 20. At each step of the numerical analysis, numerous uncertainties or unknowns had to be covered by conservative assumptions. Idealized closed-form solutions were also used to obtain first-approximation data.

3.1.4.1 Problem Definition

To estimate the minimum plug length required for radionuclide release compatible with NRC draft rules, the following methodology was used:

- Estimation of the maximum credible concentration in the repository for the most critical transuranic and non-transuranic isotopes.

- Numerical modeling of radionuclide migration through the plug using the theory of mass transport through a saturated porous medium. The concentrations of radionuclide compared with maximum allowable concentration defined in NRC draft 10 CFR 20 were determined with no assumptions for the discharge area characteristics and should be considered to be concentrations in the plug.

3.1.4.2 Selection of Radionuclides for Numerical Analysis

In this preconceptual analysis, radionuclides were selected from a consideration of the half-life of radioisotopes, choosing those with potentially more critical concentrations at the end of plugs. Table III gives a list of the radionuclides choosen and summarizes decay characteristics and concentration limit within the boundary or restricted area defined by NRC draft document 10 CFR 20, Appendix B (Table II, column 2).

3.1.4.3 Maximum Credible Concentration of the Radionuclides in the Repository

To estimate the quantity of radionuclides escaping from the canisters, the following assumptions were made:

(1) Three waste-fuel assemblies per canister;

(2) A 10-year cooling period before storing the canisters in a repository;

(3) When a waste package fails, the total amount of radionuclides present in the canister is dissolved in the ground water;

TABLE III

RADIONUCLIDES CHOSEN IN NUMERICAL ANALYSIS

Isotope	NRC* Maximum Allowable Concentration (mμCi/ml)	Half-life (years)
C_{14}	8×10^{-4}	5.73×10^{3}
I_{129}	6×10^{-8}	1.57×10^{7}
U_{238}	4×10^{-5}	4.51×10^{9}
Pu_{239}	5×10^{-6}	2.44×10^{4}
Am_{241}	4×10^{-6}	4.58×10^{2}
Np_{237}	3×10^{-6}	2.16×10^{6}

*Value from 10 CFR 20, Appendix B, Table II, Column 2: concentration limit within the boundary of the restricted area.

(4) The surrounding basalt rock is a no-flow boundary; and

(5) The volume of water per failed canister in which radionuclides are dissolved is computed by assuming a 15-m failed waste package spacing and equals the amount of ground water necessary for filling the void of a 15-m long by 7-m diameter repository section backfill material having an effective porosity of 0.33 (Figure 70).

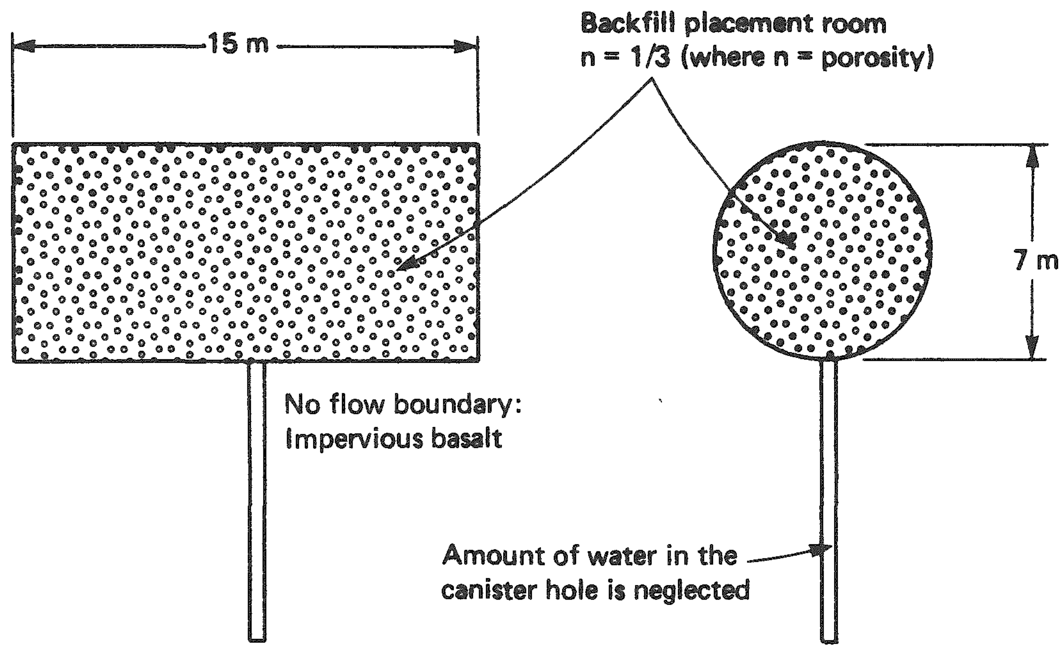
Assumptions 3 and 5 are believed to be highly conservative, and concentrations of listed radionuclides are expected to be less than the corresponding maximum credible concentration summaries provided in Table IV.

3.1.4.4 Radionuclide Migration Through the Plug

The theoretical approach used to model the migration of dissolved radioisotopes through a saturated porous medium was developed by Aikens and others (1979) for shallow land burial trenches. This modeling includes the reduction of radionuclide concentration by dispersion, sorption, and decay of radioactive isotopes in space and time. In this approach, the movement of the dissolved ions through the subsoil is described by three hydraulic parameters:

(1) The hydraulic velocity, which describes the movement of the transporting ground water through the subsoil;

(2) The dispersion coefficient, which describes the movement of the radionuclide caused by the spatial gradient of the radionuclide concentration; and



Volume of ground water in backfill void: $\frac{\pi \times 7^2 \times 15}{3 \times 4} = 1.92 \times 10^8$ ml

FIGURE 70

VOLUME OF WATER PER FAILED CANISTER

TABLE IV

MAXIMUM CREDIBLE CONCENTRATION WITHIN THE REPOSITORY

Isotope	Curies/Spent-Fuel Assembly at 10 Years Cooling Time	Maximum Credible Concentration in Repository (mμCi/ml)
C_{14}	2.5 x E-1[a]	3.91 E-3
I_{129}	8.4 x E-3[a]	1.31 E-4
U_{238}	1 x E-5[b]	1.56 E-3
Pu_{239}	5.2 x E-4[a]	8.11 E-2
Am_{224}	1.2 x E-3[a]	1.87 E-1
Np_{237}	4.3 x E-1[a]	6.70 E-1

a From ERDA 76-43, Table 2.4

b Calculation made assuming 3 x 10^5 g per assembly

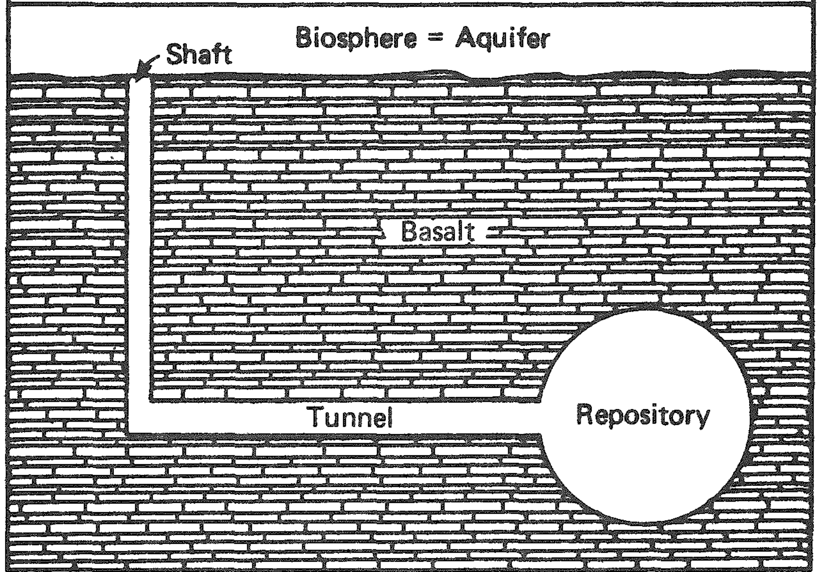
(3) The retardation coefficient, which describes the ability of the subsoil to impede by sorption the movement of a specific radionuclide.

Preconceptual design assumptions, given in Figure 71, were used to approximate the complex problem of the migration of dissolved radionuclide through the plug and its environment as a one-dimensional problem, modeled by one-dimensional, half-space medium, mass transport equations. The solutions for the equations were proposed by Aikens and others (1979) and are given in Appendix C, using the following additional radiological, thermomechanical, and hydrological design assumptions to obtain closed-form, analytical solutions:

- The initial radioactivity of the contents of the repository decays with time. It is also constantly depleted by dissolution of radionuclides in the ground water and by migration through the plug and out of the repository. These phenomena affect the concentration of contaminant by defining a time-dependent behavior of the source term. However, for this study, and because closed-form analytical solutions can only be obtained when steady state conditions are reached, a constant source term has been used. Thus, the quantity of radionuclides available for migration has conservatively been assumed to be constant with time.

- The concentration of contaminant at the beginning of the plug is assumed to be the same as that in the repository close to the waste canister; thus, dispersion and sorption phenomena are neglected in the repository.

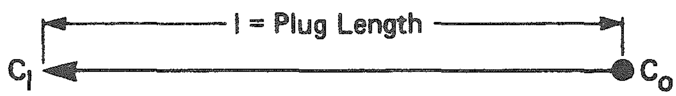
PROBLEM BOUNDARY CONDITIONS



ASSUMPTIONS

- The bedrock surrounding the plug and the disturbed zone is a no-flow boundary.
- The length of the flow path is equal to the length of the plug.
- The plug material is homogeneous and isotropic.
- The transversal dispersivity is neglected.
- The hydraulic parameters are time- and space-averaged.
- Shaft and tunnel are assumed identical in size and shape.

NUMERICAL MODEL



One-Dimensional Half-Space Porous Medium

FIGURE 71

NUMERICAL MODELING OF MASS TRANSPORT THROUGH THE PLUG

- The interaction behavior of radionuclides has been neglected; thus, the sorption capability of the medium for one specific radionuclide is independent of the concentration of the other radionuclides.

- The ground water is incompressible and remains at constant viscosity in space and time.

- The thermal loading generated by the activity of the contaminants has not been taken into consideration in this study, although hydrogeological parameters and plug characteristics are sensitive to temperature change and temperature gradient.

- The plug is saturated.

With these assumptions, the solution of the mass transport equations give a relation between (1) the length of plug required so that the maximum credible concentration of each specific radionuclide at the end of the plug is equal to the concentration limit defined by NRC regulations; and (2) the hydrological and radiological design parameters (see Appendix C). This relation is defined by the following:

$$\ell = \frac{2a}{\Theta} \ln \frac{C_o}{C_\ell} \qquad (3.31)$$

where ℓ = length of the plug

α = dispersivity coefficient

c_o = concentration of the radionuclide at the plug face

c_ℓ = concentration limit of the radionuclide

$$\Theta = \sqrt{1 + \frac{4\lambda\alpha R}{V}} - 1 \qquad (3.32)$$

where λ = decay constant of the radionuclide
α = dispersivity coefficient
R = retardation coefficient
V = hydraulic velocity of the ground water.

Half-life of radionuclide, initial concentration at the plug face, and concentration limit values are presented in Tables III and IV for the selected radioisotope.

3.1.4.5 Hydraulic Parameters - Selected Values for Plug

A discussion explaining the choice of Hydraulic Velocity, Dispersion, and Retardation Coefficients follows:

(i) Hydraulic Velocity

If the length of the plug is long enough, compared with its transverse section, the average hydraulic velocity of the ground water in the plug can be determined by using Darcy's law:

$$V = \frac{1}{n} K_i \qquad (3.33)$$

where: V = hydraulic velocity (cm/sec)
n = effective porosity
K = permeability (cm/sec)
i = hydraulic gradient.

Laboratory tests were conducted to provide quantitative values of porosity and permeability of preferred candidate plug materials. For soil backfill and concrete plugs, porosities between 0.2 and 0.4 and permeability coefficients ranging between 10^{-8} and 10^{-9} cm/sec have been reported. However, preliminary analyses (presented in Sections 3.1.2 and 3.1.3) show the extreme importance of the disturbed zone permeability in the plug/host rock seepage analysis. In this study, the average values chosen are 1/3 for the effective porosity and 10^{-7} cm/sec for the hydraulic conductivity coefficient. For Iodine 129, a length of plug calculation will also be done for a 10^{-8} cm/sec hydraulic conductivity to evaluate length of plug sensitivity to a decrease in permeability. In all the computations, the space- and time-averaged hydraulic gradient is 10^{-3}. This value was proposed as a preconceptual datum for the long-term horizonal hydraulic gradient in the repository in basalt (see Appendix A).

(ii) Dispersion Coefficient

The dispersion coefficient is a measure of the movement of the radionuclide in relation to the movement of the ground water. The dispersion of the contaminant is caused principally by molecular diffusion and hydrodynamic dispersion (NUREG, 1979). Molecular diffusion takes place where an unequal distribution of contaminant exists in a limited volume of water. This parameter has been neglected in the present study. Hydrodynamic dispersion is principally caused by variation of velocity in the ground-water system and may be approximated using the following relation:

$$D = \alpha V \qquad (3.34)$$

where V = hydraulic velocity of the ground water

α = longitudinal dispersivity of the porous medium.

In absence of laboratory test data for specific referred plug material, a mean value for α of 3.048 m has been chosen, based on data from the literature (Aikens and others, 1979; NUREG, 1979).

(iii) Retardation Coefficient

Retardation of radionuclide migration through a porous medium means that the rate of migration of the radionuclide is slowed to less than the rate of the ground water. Retardation is principally caused by sorption phenomena between the contaminant and the porous medium. The retardation coefficient depends on the distribution coefficient K_d:

$$R = 1 + (1-n)\ K_d/n \qquad (3.35)$$

where n is the effective porosity of the porous medium, and Kd can be approximated by:

$$K_d = \frac{A}{100} \times \frac{Q}{Ce} \qquad (3.36)$$

where A = the dimensionless cation sorption equilibrium constant
Q = the cation exchange capacity (mEq/100 g)
Ce = total cation concentration (mEq/ml).

Distribution coefficients are strongly dependent on the chemical nature of the radionuclide. Estimated values given in Table V for a typical desert soil indicate, for example, a

TABLE V[a]

ESTIMATED DISTRIBUTION COEFFICIENTS IN A TYPICAL DESERT SOIL

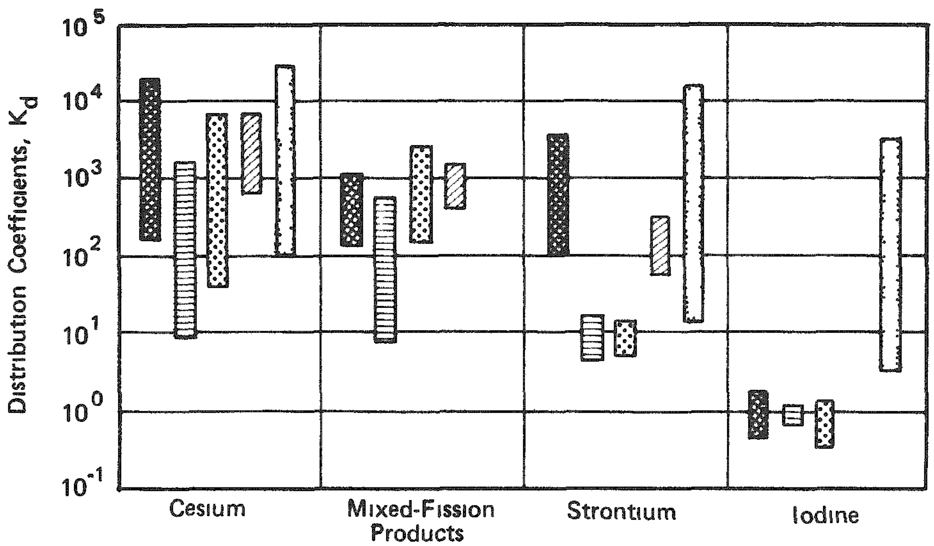
Atomic No.	Element	K_d (ml/g)[b]	(1/R)[c]
1	Tritium	0	1
4	Beryllium	75	3×10^{-3}
6	Carbon	2	1×10^{-1}
11	Sodium	10	2×10^{-2}
17	Chlorine	0	1
18	Argon	0	1
19	Potassium	35	6×10^{-3}
20	Calcium	15	1×10^{-2}
26	Iron	150	3×10^{-4}
27	Cobalt	75	3×10^{-3}
28	Nickel	80	3×10^{-3}
34	Selenium	20	3×10^{-2}
36	Krypton	0	1
37	Rubidium	125	2×10^{-3}
38	Strontium	20	1×10^{-2}
39	Yttrium	2,000	1×10^{-4}
40	Zirconium	2,000	1×10^{-4}
41	Noibium	2,000	1×10^{-4}
42	Molybdenum	5	4×10^{-2}
43	Technetium	0	1
46	Paddadium	250	9×10^{-4}
48	Cadmium	2,000	1×10^{-4}
50	Tin	250	9×10^{-4}
51	Antimony	15	1×10^{-2}
53	Iodine	0	1
55	Cesium	200	1×10^{-3}
61	Promethium	600	4×10^{-4}
62	Samarium	600	4×10^{-4}
63	Europium	600	4×10^{-4}
67	Holmium	600	4×10^{-4}
81	Thallium	2	1×10^{-1}
82	Lead	4,000	6×10^{-5}
83	Bismuth	10	2×10^{-2}
84	Polonium	25	9×10^{-3}
85	Astatine	0	1
86	Radon	0	1
87	Francium	200	1×10^{-3}
88	Radium	100	2×10^{-3}
89	Actinium	1,000	2×10^{-4}
90	Thorium	15,000	2×10^{-5}
91	Protactinium	4,000	6×10^{-5}
92	Uranium	3,000	7×10^{-5}
93	Neptunium	15	1×10^{-2}
94	Plutonium	2,000	1×10^{-4}
95	Americium	2,000	1×10^{-4}
96	Curium	600	3×10^{-4}
97	Berkelium	700	3×10^{-4}

[a]From Aikens and others (1979)
[b]Equilibrium distribution coefficients between water and soil.
[c]Inverse of retardation coefficients

difference of four orders of magnitude between distribution coefficients of iodine and plutonium. The distribution coefficients are equally affected by the sorptive capacity of the medium, as shown in Figure 72 where a range of values of the distribution coefficient are given for various rock types and various radioisotopes. Distribution coefficients for Iodine are reported to vary from 1 for a granite or a limestone to 5,000 for a high sorptive soil. For a specific radionuclide, the highest retardation coefficient can be expected for a backfill (including clay montmorillonite or zeolite, considering their high exchange capacity). However, as stated by Schneider and Platt (1974), a side effect of sorption is that exchangeable ions are released from the medium into solution and can compete with the waste material for available exchange capacity. Values of retardation coefficients corresponding to estimated values for a typical desert soil (see Table V) will be used in the following numerical analysis. They are certainly conservative in the case of a soil plug, but no published data were found available for a concrete material. It is expected that these values can provide a first estimate of the retardation phenomena in a multizone soil-concrete plug. For Iodine 129, a length of plug computation will also be done, taking 10 as an average value of the plug retardation coefficient, to simulate a high sorptive montmorillonite, zeolite backfill plug.

3.1.4.6 Numerical Analysis Summary and Results

Results of computations for selected radionuclides and for the various assumed hydraulic parameter values (defined in Figure 73) are given in Appendix D.



EXPLANATION

Tuff

Granite

Limestone and Dolomite

Basalt

Soils

After Grove (1970)

FIGURE 72

RANGES OF DISTRIBUTION COEFFICIENTS FOR VARIOUS ROCK TYPES

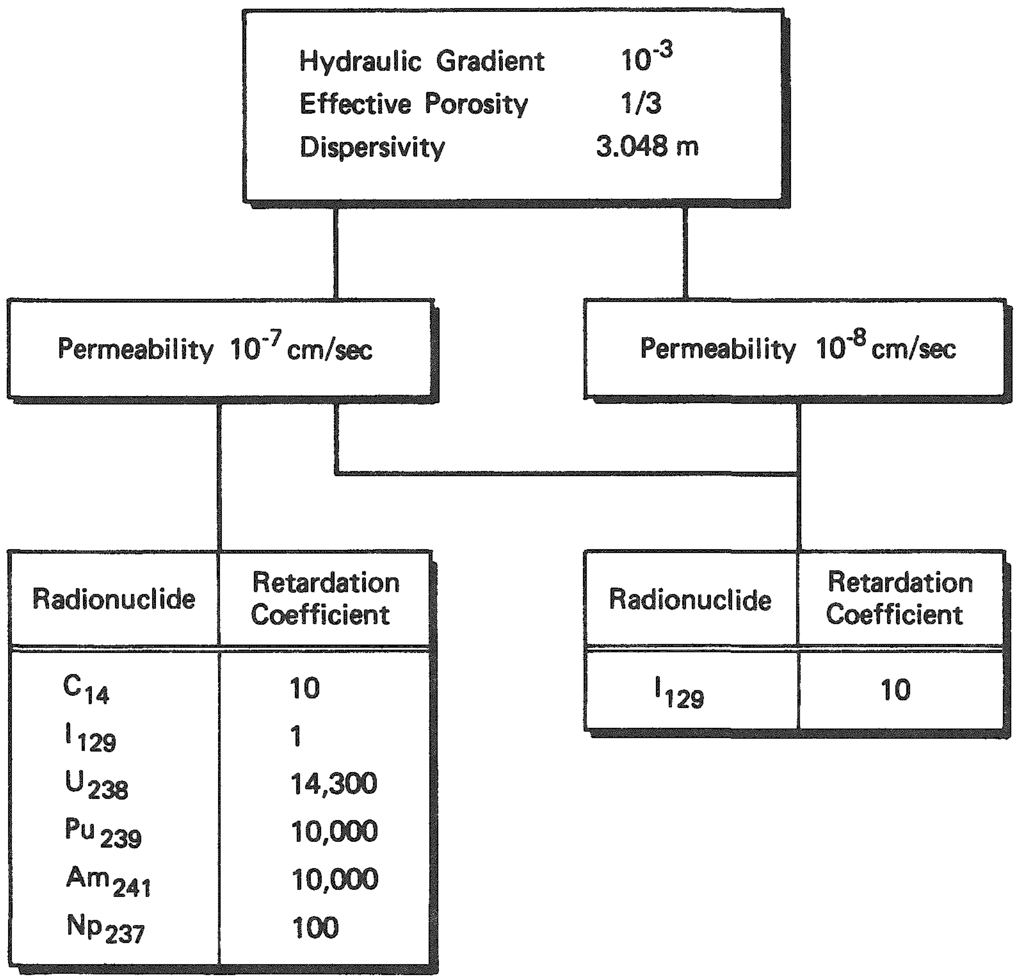


FIGURE 73

PROPOSED USE OF HYDRAULIC PARAMETERS

The minimum lengths of plug required to keep the concentration of contaminant at the end of the plug below NRC draft 10 CFR 20 concentration limits were first computed with the following assumed radiological hydrological conditions:

- Concentration of contaminant in the repository is assumed to be equal to estimated maximum credible concentrations given in Table IV; and

- Retardation coefficients are assumed to be equal to the estimated values given in Table V.

With these assumptions, the minimum lengths computed are as follows:

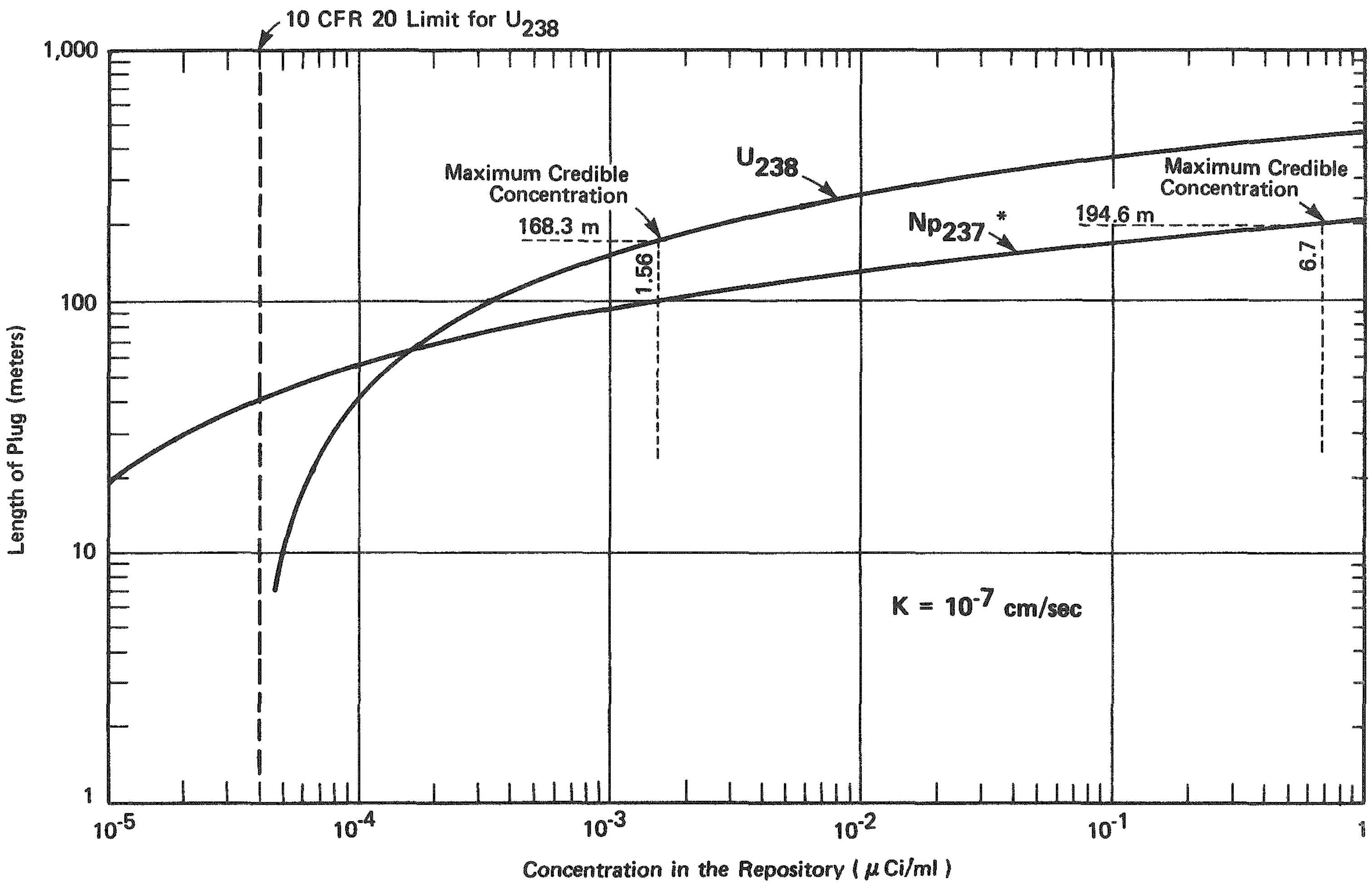
C-14:	0.8 m	U-235:	168.3 m
Pu-239:	0.6 m	Np-237:	194.6 m
Am-224:	0.1 m	I-129:	1,6507 m

The estimated minimum required lengths of plug are very small for carbon, plutonium, and americium, while the required lengths are significant for uranium and neptunium and extreme for the Iodine.

A sensitivity study was done on the uranium and the neptunium to estimate the variation of the required length of plug in relation to the concentration in the repository. Curves given in Figure 74 for neptunium and uranium using numerical values given in Appendix D show that for an increase of two orders of magnitude of the concentration of either uranium or neptunium, a plug only twice as long is required. In addition, because permeability and retardation coefficients taken in this analysis do not describe optimum plug material performance, the

FIGURE 74

LENGTH OF PLUG REQUIRED FOR 10 CFR 20 CONCENTRATIONS AT END OF PLUG



*10 CFR 20 Limit for Np_{237} is 3×10^{-6} μ Ci/ml minimum lengths shown in Figure 74 should give an acceptable upper limit for preconceptual plug design in the case of uranium or neptunium.

For the iodine, the numerical modeling gives an estimated plug length of 16 km. As shown on Figure 75, curve A, even if the concentration in the repository is three orders of magnitude less than the maximum credible concentration assumed, the required length of plug is still 4 km. Therefore, a higher performance plug is required. Two potential ways to improve plug performance are: (1) to decrease the permeability; or (2) to increase the retardation characteristics of the plug.

The analytical formulation of the required length of plug given by Equation 3.31 indicates that equivalent plug length is influenced by increasing the retardation coefficient or by decreasing the permeability, in the same order of magnitude. For the specific case of iodine, the numerical analysis shows that plug length is directly proportional to an increase in the retardation coefficient or a decrease in the permeability coefficient.

Computations leading to a 16-km-long plug were done for a non-sorptive material with respect to the iodine ($R = 1$) and for a relatively permeable plug ($K = 10^{-7}$ cm/sec). According to plug material permeability test data and according to range of distribution coefficients given by Grove (1970) for iodine in soils (see Figure 72), it seems feasible to construct a more efficient plug.

As shown in Figure 75, curves B and C indicate: (1) with a retardation coefficient $R = 10$ (alternately, $R = 1$) and a plug hydraulic conductivity of $K = 10^{-7}$ cm/sec (alternately

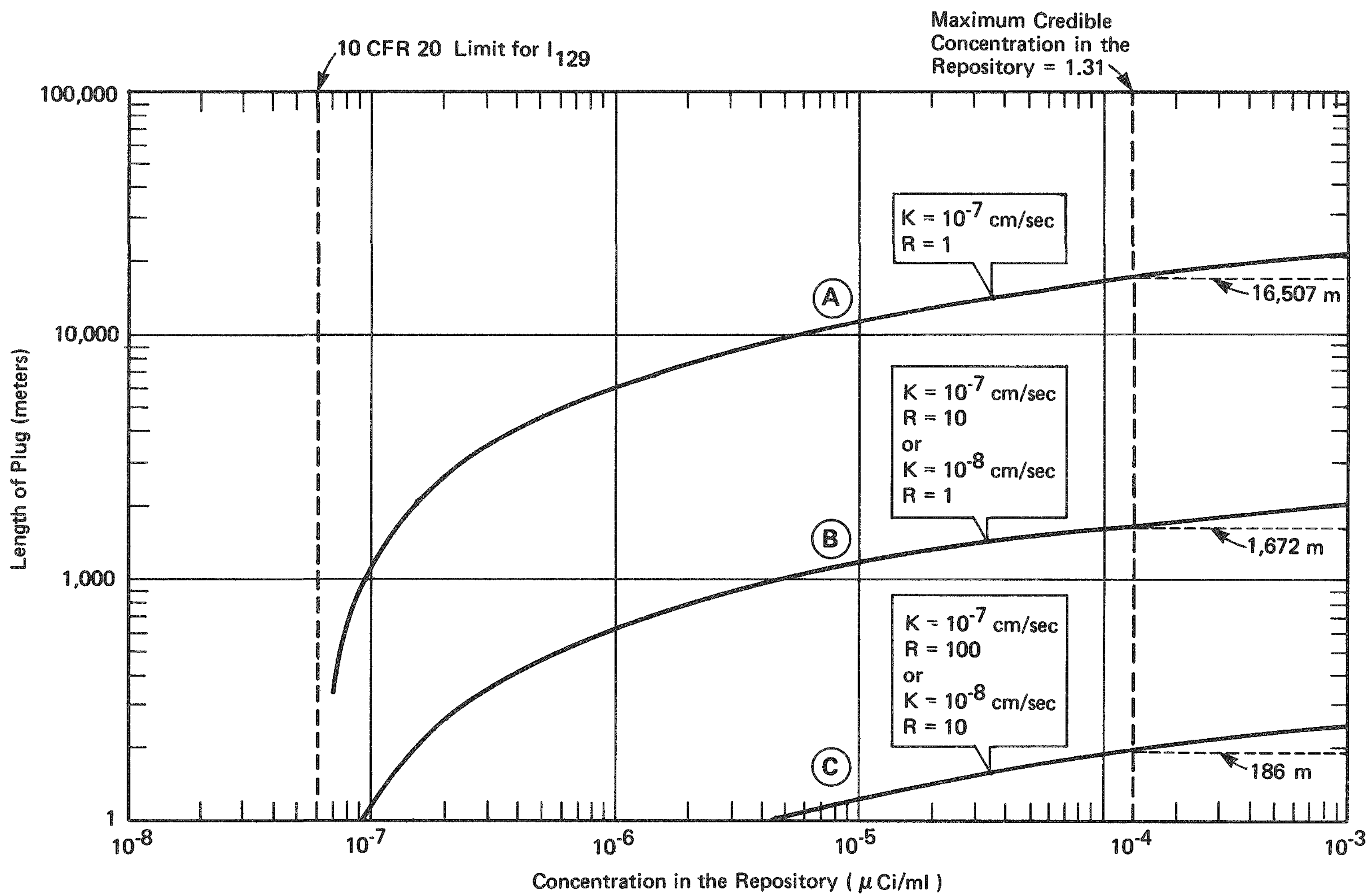


FIGURE 75

LENGTH OF PLUG REQUIRED FOR 10 CFR 20 CONCENTRATIONS AT END OF PLUG AND SENSITIVITY STUDY FOR IODINE—129 WITH RESPECT TO K AND R

$K = 10^{-8}$ cm/sec), the estimated length of plug is then 1,620 m; (2) with a retardation coefficient R = 100 (alternately R = 10) and a plug hydraulic conductivity of $K = 10^{-7}$ cm/sec (alternately $K = 10^{-8}$ cm/sec), the required plug length is then less than 200 m. This equal and direct dependence of plug performance with plug permeability and plug sorptive ability provides guidelines to optimize plug design; it also indicates that quality control will be of primary importance to ensure acceptable plug performance.

3.1.5 Cost and Feasibility Analysis of Preconceptual Plugging Schemes

A study of the candidate schemes in sufficient detail to arrive at an estimated cost was done to establish a useful ranking of the schemes. The detail steps of contacting industrial equipment and materials suppliers, reviewing the skilled labor needs, and estimating production methods and rates provided an initial feasibility check and a quantified measure of construction complexity (i.e., cost). It was found during the evaluation that three schemes, all involving melt-in-place metal plugs, were not considered feasible on the basis of industrial experience, which showed damaged rock environments at the temperatures and pressures involved.

The construction complexity factor of cost was used as one of the rating factors in a later comparative analysis of systems to identify the best candidate schemes for preconceptual plug designs.

3.2 DOMINANCE ANALYSIS

This section of the report presents results and data for a final technical analyses of the monolithic plug schemes, within the scope of the preconceptual design program, and uses an extended dominance analysis technique to demonstrate the relative superiority of individual candidate schemes in key design function areas.

Using the results of the extended dominance analysis, various superior-performing monolithic plug schemes will be incorporated into multiple-zone plug systems to secure an improved, overall plug performance (with regard to the key design function areas) that is not achievable with monolithic plugs alone. Note that these multiple-zone plug systems will not necessarily coincide with the multiple-zone plug schemes discussed up to this point.

3.2.1 Technical Data for Dominance Analysis of Candidate Monolithic Plug Schemes

Radionuclides can potentially migrate past a plug (Figure 76) in any one or a combination of the following three ways:

- By migration through the plug;
- By migration through the plug/rock interface; and/or
- By migration through the disturbed rock surrounding the plug.

In the actual case, all three paths would probably contribute toward any total migration that might occur. A well-designed plug system would minimize the extent of available flow paths (e.g., low permeability, good plug/wall rock contact, and

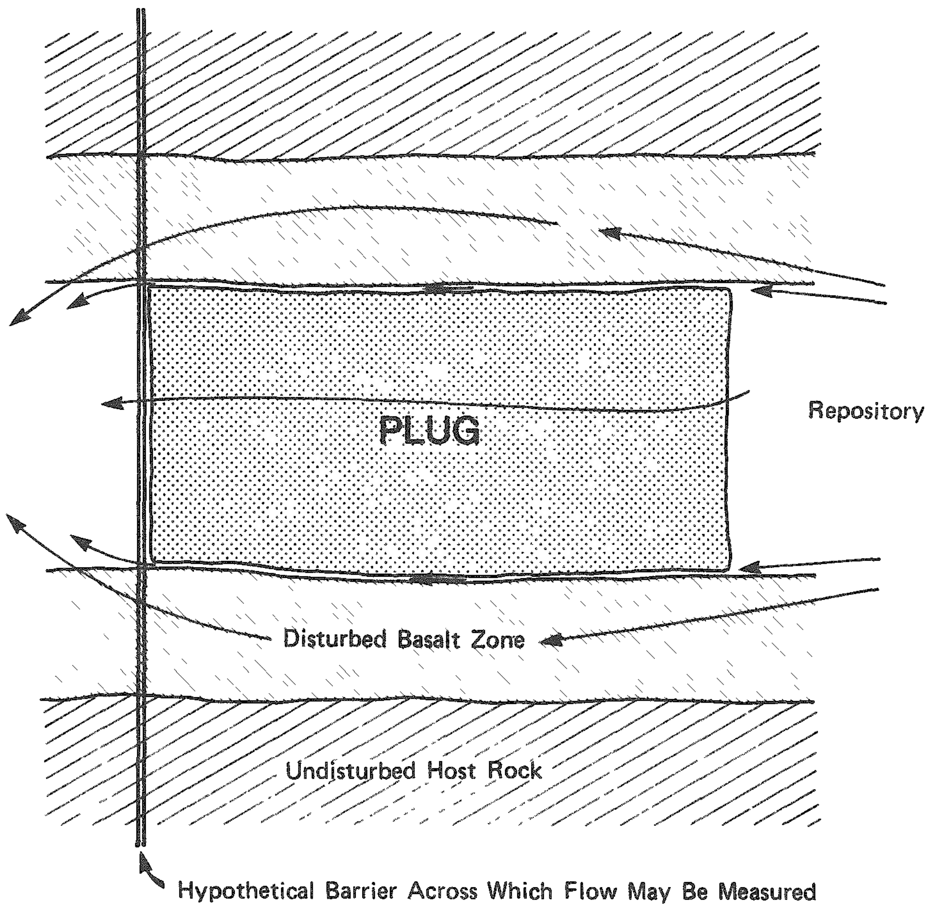


FIGURE 76
MIGRATION OF RADIONUCLIDES ACROSS A HYPOTHETICAL PLUG

integration of plug materials into any disturbed rock surroundings) and must be stress and strain compatible with the host rock to maintain its performance under lithostatic and thermomechanical stress changes that may occur after construction.

3.2.1.1 Analytical Approaches and Required Design Parameters

A well-designed plug is dependent on the chosen values for two types of design parameters:

- Assumed constant design parameters, which include the spatial arrangement of the waste disposal; the shape and size of the tunnels, shafts, and boreholes; the characteristics of the radioactive source; and the lithostatic state of stress.

- Design parameters sensitive to variations in plug material, plug placement technology, and plug scheme concept.

The performance of two plug schemes can be evaluated by comparing expected values, or range of values, for the design parameters of the second category and judging the final impact of this variation on the overall plug performance. For each plug zone considered, Table VI gives the theoretical approach chosen and the corresponding design parameters sensitive to variation in plug material and/or plug-placement technology. Some of the parameters listed are commonly used in civil, mining, or hydraulic engineering, and field or laboratory data are readily available, while others required special testing to obtain data due to specific conditions in plug design for waste disposal. A few design parameters are specific to plugging

TABLE VI

PLUG EVALUATION DESIGN PARAMETERS

Plug Zone Considered	Analytical Approach	Design Parameters
Plug	Mass transport* through saturated porous medium	Dispersion coefficients Retardation coefficients
Plug/wall rock interface	Sliding stability	Bond strength Swelling-shrinkage (soil plug) Expansion-shrinkage (cement plug)
	Linear thermoelasticity (plug environment and elastic plug)	Young's modulus Poisson's ratio Coefficient of thermal expansion
	Consolidation theory (soil-plug)	Compressibility Coefficient of thermal expansion Void ratio
Disturbed zone extent	Linear thermoelasticity	Young's modulus Poisson's ratio Coefficient of thermal expansion
Disturbed zone treatment	Flow-through saturated porous medium	Cutoff collar or grouting treatment Influence on disturbed zone Permeability

* Porosity and flow or permeability and flow

boreholes and, when available, quantitative data for these parameters were chosen for different specific conditions and locations.

(i) Design Parameters to Assess Mass Transport in Porous Medium

Design parameters necessary to describe the flow of radionuclides dissolved in ground water through a saturated porous medium include the effective porosity, the permeability, the dispersion, and the retardation coefficients. Permeability and porosity are basic parameters in any hydraulic application. Dispersion and retardation coefficients are less well understood in geotechnical design and are discussed following (see Section 3.1.4.5).

The dispersion coefficient is a measure of the movement of contaminant caused by the spatial gradient of the contaminant concentration. The few published data on dispersion coefficients were generally determined for specific soil sites. No data are specifically available for the selected candidate plugging materials.

Retardation coefficient is a measure of the capacity of a porous medium to slow down the rate of migration of a contaminant through the medium. Retardation is principally caused by sorption phenomena between the contaminant and the porous medium.

(ii) Design Parameters to Assess the Thermomechanical Behavior of the Plug

For an elastic plug (basalt, concrete, grout, metal) and when using the theory of differential linear thermoelasticity, the design parameters necessary to describe stress concentration in the plug and its environment include the thermal expansion coefficient, Young's Modulus, and Poisson's Ratio of the plug and the host rock container. Stress concentrations are calculated and compared with maximum strength criteria. The maximum strength is affected by the confirming pressure, the temperature, and the moisture content of the materials.

The problem of analyzing the performance of non-linear, elasto-plastic plug (bentonite mixture or compacted soil backfill) is more difficult. An approach using the theory of consolidation to describe the plug behavior may be useful but will have to be done in a later study. Design parameters in this case include the initial void ratio and the compression index of the plug material. Stress concentration in the plug environment may be approximated from the theory of elasticity and compared to the maximum strength of the plug material; however, performance criteria for the plug itself should probably be expressed in terms of the maximum allowable radial deformation of the plug required to minimize disturbance rock zone around the plug. Additionally, there is no easy way to evaluate the thermally induced volume change of a soil in a tunnel or a shaft. Factors such as thermal consolidation or swelling can strongly affect the residual amount of non-elastic deformations. Moreover, thermal expansion and compressibility coefficients of a soil material, such as a compacted backfill or a soil bentonite slurry, depend on specific problem boundary conditions. Modeling must ultimately be done in the laboratory to provide quantitative data by simulating in-situ stresses, temperature, and drainage.

(iii) Design Parameters to Assess the Sliding Stability of a Plug

The primary design parameter involved in describing sliding stability of a plug is the bond strength between the plug and the plug/wall rock interface. However, such bonding is affected by various physiochemical plug/wall rock interactions and may vary with factors such as the initial plug placement condition (dry hole, wet hole, mud-contaminated hole), the volumetric stability of the plug material (swelling of clayey backfill, shrinkage of concrete), and the stress and strain field around the plug/wall rock interface induced by the thermomechanical loading of the waste canisters and the lithostatic stress field. In this preconceptual study, bonding between the plug material and wall material and the wall rock interface has been experimentally determined by measuring the force necessary to extrude a miniature, simulated model plug from its basalt container. The bond strength was equated to this force, divided by the contact area between plug and wall rock. This bond strength must be compared with the shear stress developed along the plug/wall rock interface due to differential water head, steam pressure applied in the plug radial section, and shear stresses generated by thermal loading along the bonding surface.

(iv) Other Design Parameters

Some design parameters were not directly taken into consideration in the idealized approaches used, but a knowledge of such data can be useful for plug scheme evaluation. These parameters include density of the plug material, which will be considered in quality control assessment, and swelling pressure developed by backfill because a high swelling pressure indicates a good self-healing potential of the candidate material and a better contact between plug and host rock.

(v) Selected Design Parameter Values

Table VII summarizes the range of values of design parameters for preferred candidate materials. For basalt, proposed values were taken from Appendix A, while the values for cementitious mixtures and compacted earthen materials and soil bentonite slurries were selected after reviewing project-related literature and comparing published values with values obtained in the physical testing program of this study. Values proposed for the basalt block with mortared joints were computed after assuming the geometry and shape of the block and the thickness of the joint. A 0.195 m by 0.195 m by 0.095 m block, having an average weight of 91 kg and a 1-m-thick mortar joint, was considered. Values proposed for the compressed bentonite block with dry-packed bentonite joints were based on data from the physical testing program on highly compacted, montmorillonite-rich, clay material. Where a question mark is shown, no value of the design parameter is proposed, indicating that no consistent published data have been found and no in-house testing was done to determine this unknown.

3.2.1.2 Technical Rating of Candidate Monolithic Plug Schemes

Using the above mentioned design parameters, quantitative ratings were developed for the estimated performance of each monolithic plug scheme. A total of five design functions were selected to describe total plug performance over the range of

TABLE VII

PROPOSED VALUE OF DESIGN PARAMETERS

DESIGN PARAMETERS / PLUG MATERIALS	Porosity, percent	Permeability (cm/sec)	Cation exchange capacity (meq/100g)	Young's modulus (MPa)	Poisson's ratio	Thermal expansion (°C)	Unconfined compressive strength (MPa)	Compression index, c	Bond strength (MPa)	Swelling pressure (MPa)	Density (g/cc)
Basalt	1.24	10^{-9}	4/9.3	$>>10^{3}$	0.25	6.2 10^{-6}	288	NA*	30	NA	2.78
Concrete (75-mm maximum aggregate)	25/30	10^{-7}/10^{-8}	<40	20 10^{3}/40 10^{3}	0.15/0.20	10^{-5}	30/40	NA	3/10	NA	2.2/2.5
Concrete (10-mm maximum aggregate)	25/30	10^{-8}/10^{-9}	< 40	20 10^{3}/40 10^{3}	0.15/0.20	10^{-5}	30/40	NA	3/10	NA	1.5/2.0
Cement slurry	25/30	10^{-7}/10^{-8}	<40	20 10^{3}/30 10^{3}	0.15/0.20	10^{-5}	20/30	NA	3/10	NA	1.5/2.0
Stiff clayey mixture (75-mm maximum aggregate)	20/30	10^{-7}/10^{-8}	20/80	40/60	0.20/0.40	?	1/3	0.05	0.5/1	0/3	2.2/2.4
Stiff clayey mixture (10 mm maximum aggregate)	20/30	10^{-8}/10^{-9}	20/80	40/60	0.20/0.40	?	1/3	0.05	0.5/1	0/3	2.2/2.4
Clay mixed with sand and silt	25/35	$<10^{-8}$	60/100	40/60	0.30/0.50	?	1/3	0.7	0.2/1	0/3	1.8/2.2
Soil bentonite slurry	30/35	10^{-7}/10^{-9}	60/100	Very small	0.30/0.50	?	Very small	1/3	0	0	1 6/1.9
Basalt block with mortared joints	5	10^{-8}/10^{-9}	4/9.3	70 10^{3}/75 10^{3}	0.25	$>10^{-6}$	?	NA	3/5	NA	2.7
Compressed bentonite blocks, dry sack joints with bentonite	20	$<10^{-9}$	>80	60	0.30/0.50	?	5	1	0.5	~3	2.2

*NA = non applicable

plug environments (i.e., tunnels, shafts, and boreholes), and include the following:

- Core barrier performance;
- Plug/wall rock performance;
- Disturbed zone cutoff performance;
- Mechanical stability performance; and
- Long-term integrity.

The design parameters that were used to analyze the general performance of a plug with respect to these functions are listed on Tables VIII through XII. The tables provide numerical rating values corresponding to levels of possible parameter values; in general, the better the functional performance of an individual parameter, the higher the numerical rating.

These numerical values were put into rating matrices that were prepared for each design function pertinent to each of the three plug environments (i.e., five design function rating matrices for tunnel plugs, four matrices for shaft plugs, and three matrices for borehole plugs). Included in these matrices were: (1) all the machine and material combinations identified as being most feasible or possible at this time with little or no modification for the particular plug environment being considered; and (2) all the parameters identified in Tables VIII through XII as being pertinent to the particular design function being rated. One of these matrices is shown as Table XIII and the remaining 11 matrices are shown in Appendix E.

The design function rating matrices were completed by first referring to the general details of the plugging schemes in

TABLE VIII

PLUG BARRIER PERFORMANCE

Parameters	Scale	Description
Ion exchange capacity (absorptive capability of plug)	0 1 2	Low (5 to 40 mEq./100 g) Moderate (40 to 80 mEq./100 g) High (80 mEq./100 g)
Permeability of plug material as determined in laboratory tests (K in cm/sec)	1 2 3	$10^{-7} \leq K < 10^{-8}$ $10^{-8} \leq K < 10^{-9}$ $K < 10^{-9}$
Uniformity of permeability through plug	0 1 2	2 orders of magnitude 1 order of magnitude Uniform

TABLE IX

PLUG/WALL ROCK INTERFACE PERFORMANCE

Parameters	Scale	Description
Sliding stability	0	Sliding stability is non-existent or has to be demonstrated
	1	Acceptable long-term or short-term sliding stability
	2	Acceptable long-term and short-term sliding stability
Plug/wall rock continuity after cyclic thermomechanical loading	0	No continuity
	1	Moderate continuity
	2	Expected continuity if plug confined
	3	Good continuity
Reliability of interface joint closure during construction	0	Poor reliability
	1	Moderate reliability
	2	Good reliability
	3	Good reliability and self-healing potential

TABLE X

PLUG AND DISTURBED ZONE MECHANICAL STABILITY PERFORMANCE

Parameters	Scale	Description
Plug mechanical stability under in-situ thermomechanical loading	0	No stability
	1	Stable when plug confined (no axial movement)
	2	Stable even when plug is not confined
Long-term wall rock support	0	No long-term support provided
	1	Long-term suport provided by plug strength resistance or by expansive properties of plug
	2	Long-term support provided by plug strength resistance and expansive property of plug

TABLE XI

PLUG LONG-TERM INTEGRITY PERFORMANCE

Parameters	Scale	Description
Solubility	0	Affected by pH 7 to 10
	2	Stable in pH 7 to 10
Documented history of survival	0	Less than 2,000 years of relevant documented history of survival with no analogs of similar material in nature
	1	Man-made material; an analog or the actual material can be documented for 2,000 years
	2	Natural material; survival history of millions of years in nature
E_h	1	Stable under oxidizing conditions (E_h of environment 0.0 volts)
	2	Stable under reducing conditions (E_h of environment 0.0 volts)
	3	Stable through a range of E_h conditions ranging from moderately oxidizing to reducing

TABLE XII

DISTURBED ZONE TREATMENT PERFORMANCE

Parameters	Scale	Description
Disturbed zone treatment performance	0	Cutoff collars do not improve disturbed zone treatment better than contact grouting ($K \geq 10^{-6}$ cm/sec)
	1	Cutoff collars permeability in the range of 10^{-7} cm/sec
	2	Cutoff collars permeability in the range of 10^{-8} cm/sec
	3	Cutoff collars permeability in the range of 10^{-9} cm/sec
Construction difficulty	0	Very difficult
	1	Moderate difficulty
	2	No special difficulty

TABLE XIII

TUNNEL CORE BARRIER PERFORMANCE

Scheme No.	MONOLITHIC PLUG SCHEMES — MATERIAL	MACHINE	Figure No	Ion exchange	Permeability	Uniformity	Unit cost
				PARAMETERS			
T 1	75-mm maximum aggregate in stiff clay	Large compactor and small compactor	23	1	1	0	2
T 2	75 mm maximum aggregate in concrete	Concrete pump system	22	0	1	2	1
T 3	10-mm maximum aggregate in stiff clayey mixture	Portable compactor or large compactor depending on the size of the plug	20	1	2	1	2
T 4	10-mm maximum aggregate in clay slurry mixture	Concrete pump system	22	1	2	2	1
T 5	10-mm maximum aggregate in cement mixture	Concrete pump system	22	0	2	2	1
T 6	Clay mixed with sand/silt	Portable or large compactor, depending on the size of the plug	20	2	3	1	2
T 7	Clay including pelleted bentonite mixed with sand/silt	Portable compactor	20	2	3	1	2
T 8	Clay mixed with sand/silt in slurry	Grout pump system	–	–	–	–	–
T 9	Cement mixed with sand/silt in slurry	Grout pump system	–	–	–	–	–
T 10	Solid inclusion of basalt	R & D system	24	0	3	2	0
T 11	Basalt block with mortared joints	Hand masoned block	21	0	2	2	1
T 12	Compressed bentonite block, dry pack joint with bentonite	Hand masoned block	21	2	3	2	1

Figures 8 through 24, which are keyed to machine/material combinations. Then, referring to Table VII and using engineering judgment, expected values were selected for parameters that had to be rated in the matrices. No attempt was made at this point to discriminate between the relative importance of one parameter over another. The completed matrices then became input for the extended dominance analysis.

3.2.2 Monolithic Plug Scheme Comparisons and Dominance Analysis

The monolithic plug scheme evaluation thus far has established how well any candidate scheme rates with respect to two to four parameters associated with plug performance in each of three to five design functions, the latter number depending on whether the scheme is considered for a tunnel, shaft, or borehole (its environment).

There are at least two problems facing the selection of preferred schemes for a preconceptual design at this point: (1) which scheme is the best when considering a particular design function for a specific environment; and (2) which scheme is best for the complete range of design functions for a specific environment.

The first problem, for example, arises when attempting to compare two competing schemes in the design function of "core barrier performance" in shafts and noting that one scheme performs better for the parameter of "permeability" and another scheme performs better for the parameter of "ion exchange." A quantitative measure of the relative importance of one parameter in a design function relative to another parameter cannot be precisely known at this point. If it could, a specific weighting formula might be devised to obtain a single weighted average value for all the parameters of a design function for any particular scheme that could be compared with the weighted average obtained for other schemes. Nonetheless, design intent for the various schemes implicitly assumes certain inequalities among the parameters; for example, in the design function of core barrier performance, the following inequalities were assumed for the relative importance of parameters:

permeability > cost
permeability > ion exchange.

Extended dominance analysis can be employed to sort out the task of comparing alternate schemes once such inequalities are identified, as will be explained later.

The second problem arises at the next level of selection for preconceptual designs; i.e., if the schemes satisfying a particular design function best can be identified, is it possible to then compare these plugging schemes in order to identify one scheme which is best for all required design functions in a specific environment? The difficulty is inevitable if one scheme excels in one design function while another scheme excels in a different design function (e.g., core barrier performance versus tunnel plug/wall rock interface performance in a tunnel environment). Not only is it not possible to give a specific quantitative measure of the relative importance of one design function relative to another design function, but also the level of judgment needed to make a decision about relative inequalities of importance between design functions is considered more demanding than that needed to make judgments about relative importance between parameters within a design function.

Many more factors come into play at this point, including variations that might be possible in the physical properties of the actual environment of tunnels, shafts, and boreholes and the field performance of labor, machines, and materials. The judgment of expert professionals with extensive experience in geotechnical investigation, design, and construction was used to help make decisions at this level of selection.

Extended dominance analysis was the technique used to compare and identify superior schemes from the completed design function rating matrices. Dominance is one of the fundamental concepts of decision analysis. Simply stated, an alternative "A" is said to dominate alternative "B" if it can be shown that alternative A is at least as desirable as alternative B with respect to all evaluation measures (or scenarios) and is strictly more desirable with respect to at least one measure. Use of the concept of dominance is appropriate in two situations. First, when there is a single evaluation measure with an associated range of uncertainty, alternative A is said to dominate alternative B if A is more desirable at any point within the uncertain range. Second, if several evaluation measures are associated with each alternative, then A is said to dominate B if A is at least as desirable as B on all of the measures and strictly more desirable on at least one measure. If A dominates B, then A will always score higher than B using any combination scheme of the measures, whether based on weighting and rating utility theory or any other rationale. Dominance analysis requires very few assumptions about the relationships between measures, and this makes it an important tool for comparative evaluations of the sort useful to the present study.

The object of the dominance analysis for comparing plug schemes, then, is to identify those alternatives that are dominated by one or more others, because the dominated alternatives will never be the highest ranked under any combination scheme. Dominated alternatives may still be acceptable plugging schemes; however, it is desirable to focus attention on those alternatives that appear to be most favorable.

When using dominance analysis, some alternatives may be undominated simply because they score very highly on one or two relatively unimportant measures. To address this type of occurrence, the concept of extended dominance has been developed. This extends the concept of dominance by allowing incorporation of ordinal relationships (less important than, more important than) among the measures in a rigorous manner. The details of how this is done are described in Appendix F. Essentially, it involves considering sums of variable values instead of (or in addition to) the individual values when performing the dominance analysis.

The extended dominance analysis results in groups of plug schemes identified as Group A, Group B, etc. The alternatives in Group A are preferred to the alternatives in Groups B, C, etc. The alternatives in Group B are preferred to those in Groups C, D, etc. Within each group, a complete ordering is not possible. However, for some alternatives, it may be possible to list alternatives in the same group that are always preferred.

A computational example, assumptions of ordinal relationships assumed between design function parameters, and results of the complete analysis of monolithic plug schemes for superior schemes within each of the three to five design functions in each of the three environments (tunnels, shafts, and boreholes) are given in Appendix F. These results are summarized on Tables XIV, XV, and XVI for tunnels, shafts, and boreholes, respectively.

3.2.3 Discussion of Extended Dominance Analyses Results

The implications of the results of the extended dominance analyses to the preferred preconceptual designs of plug systems are given separately for each environment (refer to Tables XIV, XV, and XVI).

3.2.3.1 Tunnels

Inspection of Table XIV will show that a superior, common performer for the combined first two design functions (core barrier performance and plug/wall rock interface performance), is a scheme employing either compressed bentonite blocks or concrete. The next required design function is support performance. The most dominant scheme employs a solid, basalt inclusion, which both the study team and the construction consultant, F.P. Bystrowski & Co., consider an R&D scheme not presently viable. The next level of dominance is shared by a concrete scheme and a basalt block masonry scheme. In view of a superior concrete rating for the combined first two categories (though shared by basalt blocks in the second category), concrete might be considered the leading choice for suiting the first three design functions.

TABLE XIV

SUMMARY OF DOMINANCE COMPUTATIONS FOR TUNNELS

Scheme No.	Material	Machine	Figure No	Core barrier performance	Plug wall rock interface performance	Support performance	Disturbed zone performance	Long-term integrity performance
	Monolithic Plug Schemes	Design Functions						
T 1	75-mm maximum aggregate in stiff clay	Large compactor and small compactor	23	C	C	C	C	A
T 2	75-mm maximum aggregate in concrete	Concrete pump system	22	B	A	B	A	B
T 3	10-mm maximum aggregate in stiff clayey mixture	Portable compactor or large compactor depending of the size of the plug	20	B	C	C	B	A
T 4	10-mm maximum aggregate in clay slurry mixture	Concrete pump system	22	B	C	C	A	A
T 5	10-mm maximum aggregate in cement mixture (expansive cement)	Concrete pump system	22	B	A	B	A	B
T 6	Clay mixed with sand/silt	Portable or large compactor, depending of the size of the plug	20	B	C	C	A	A
T 7	Clay including pelleted bentonite mixed with sand/silt	Portable compactor	20	B	B	C	A	A
T 8	Clay mixed with sand/silt in slurry	Grout pump system	–	–	–	–	A	A
T 9	Cement mixed with sand/silt in slurry	Grout pump system	–	–	–	–	A	B
T 10	Solid inclusion of basalt	R & D system	24	B	C	A	C	A
T 11	Basalt block with mortared joints	Hand-masoned block	21	B	A	B	A	C
T 12	Compressed bentonite block, dry pack joint with bentonite	Hand-masoned block	21	A	A	C	A	A

TABLE XV

SUMMARY OF DOMINANCE COMPUTATIONS FOR SHAFTS

Scheme No.	Material (Monolithic Plug Schemes)	Machine	Figure No	Core barrier performance	Plug wall rock interface performance	Support performance	Disturbed zone performance	Long-term intergrity performance
S 1	75-mm maximum aggregate in concrete	Concrete wireline system	11	E	B	B	C	B
S 2	75-mm maximum aggregate in concrete	Concrete pump system	12	E	B	B	C	B
S 3	10-mm maximum aggregate in stiff clayey mixture	Small compactor	10	C	B	B	D	A
S 4	10-mm maximum aggregate in cement mixture	Concrete wireline system	11	D	B	A	B	B
S 5	10 mm maximum aggregate in cement mixture	Concrete pump system	12	D	B	A	B	B
S 6	Clay mixed with sand/silt	Small compactor	10	A	A	B	C	A
S 7	Clay including pelleted bentonite mixed with sand/silt	Small compactor	10	A	A	B	C	A
S 8	Clay mixed with sand/silt in slurry	Concrete pump system	12	C	B	C	B	A
S 9	Solid inclusion of basalt	R & D system	19	C	B	B	E	A
S 10	Basalt block with mortared joints	Hand masoned block	23	D	B	B	C	C
S 11	Compressed bentonite block, dry pack joint with betonite	Hand masoned block	23	B	A	B	A	A
S 12	Cement slurry	Concrete pump system	12	E	B	B	C	B

Column header group: Design Functions (performance columns); Monolithic Plug Schemes (Material, Machine).

TABLE XVI

SUMMARY OF DOMINANCE COMPUTATIONS FOR BOREHOLES

Monolithic Plug Schemes			Design Functions	Core barrier performance	Plug wall rock interface performance	Long-term integrity performance
Scheme No	**MATERIAL**	**MACHINE**	**Figure No**			
B 1	10-mm maximum aggregate in stiff clayey mixture	R & D system	18	A	C	A
B 2	10-mm maximum aggregate in slurry clay mixture	Grouting system	9	A	C	A
B 3	10-mm maximum aggregate in cement mixture	Grouting system	9	A	B	B
B 4	Clay mixed with sand and silt	R & D system	18	A	C	A
B 5	Clay mixed with sand and silt in slurry	Grouting system	9	A	C	A
B 6	Cement slurry	Grouting system	9	A	A	B
B 7	Basalt solid inclusion	R & D system	21	A	C	A
B 8	10-mm aggregate with clay or bentonite slurry	R & D system	17	A	B	A
B 9	10 mm aggregate with bentonite pellets in clay slurry	Gravel pack plant	24	A	B	A

In the fourth design function of disturbed rock zone treatment, there is a wide range of possibilities in the same top dominance group. However, depending on specific design details, some schemes within the group may or may not be dominated by the other schemes. It appears, though, that in cutoff collar treatments, pumped clay/sand/silt slurry mixtures or clay/aggregate mixtures, or compressed bentonite blocks provide the more superior choices. (Pressure grouting of rock fractures has been presumed for all designs, whether or not cutoff collars are used.)

In the fifth design function of long-term integrity, compacted earth and clay slurries dominate. If concrete is used to a large extent to meet a number of the other design functions, particularly the support function, it seems necessary to consider compacted earth schemes as backup elements. However, a zoned plug of concrete and earth elements may be difficult to construct, and it was commented often during this study that it will be especially difficult to obtain good compaction and contact of earth materials at the top of tunnels. In reviewing this function to find why basalt block schemes rated so low, it appears that basalt block schemes are penalized heavily in the analyses input because of proposed cement mortar joints. Judgment suggests that the penalty may actually be too severe in view of the small included volume of mortar joints in such schemes.

In any case, considering the self-cementing properties of finely ground basalt (as determined during the geochemical test program), it might be reasonable to specify a few zones using basalt blocks with basalt mortared joints as a redundant feature to any concrete zones. This scheme might be easier to construct in tunnels and would secure improved long-term integrity features in the multiple-zone plug design. It should be noted, though, that the geochemical tests were carried out at elevated temperatures as an alternative to long-term testing for reactions. Consequently, it would be necessary to check the self-cementing property at ambient temperatures or to plan on curing the mortared block installation in the tunnel at some elevated temperature. Cement mortar will be tentatively selected at this point, although ground basalt mortar is at least recommended for future investigation.

3.2.3.2 Shafts

Inspection of Table XV shows that compacted earth schemes (or compressed bentonite blocks) rate high for the first two design functions of core barrier performance and plug/wall rock interface performance.

In the third design function of support performance, concrete schemes dominate, while in the fourth design function of disturbed rock zone treatment, concrete is a midrange possibility, dominated by compressed bentonite blocks. The principal design plan for DRZ treatment in shafts is to excavate cutoff collars through the DRZ and to backfill them with a seepage barrier material. In the shaft configuration, a cutoff collar excavation would undermine an annulus of loosened DRZ, so the excavation would have to be done in partial, arc segments with backfilling of excavated segments before excavating adjoining arc segments (much like special techniques for pulling pillars in coal mines). The cutoff collar backfill in shafts then, unlike tunnels, must carry a potentially significant load. This is not really recognized in the data input to the dominance analysis for shafts, and the compressibility of bentonite blocks might permit progressive loosening of the DRZ. The preferred choice of plug scheme for design functions three and four is concrete.

In the fifth design function, long-term integrity, compacted earth schemes dominate and concrete schemes are in a midrange. From a consideration of the makeup of the multiple-zone plug thus far envisioned for the shaft, compacted earth is already a major feature of the plug, and concrete, even if it suffers some degradation in quality with time, could still be able to perform its design functions to some extent. Thus, the plugs as a whole are expected to perform in an acceptable manner.

3.2.3.3 Boreholes

Inspection of Table XVI quickly reveals two potential zones for a multiple-zone plug that has superior performance over all the design functions necessary to borehole plugs.

The gravel and clay slurry with bentonite pellets rates among the highest in core barrier performance and long-term integrity performance, while cement grout is dominant in plug/wall rock interface performance.

3.3 EVALUATION AND JUDGMENT

Up to this point, the preconceptual plugging schemes have been subjected to a variety of analyses to determine their technical and economic feasibility and to evaluate the possible characteristics of plug performance. The engineering judgment exercised by WCC staff during these analyses was limited by the fact that it was not based on experience with actually sealing of boreholes, tunnels, or shafts leading to a radioactive waste repository. Consequently, it was necessary to solicit the judgment of knowledgeable individuals who have long experience and familiarity with different aspects of tunneling and plugging. Using a concensus of their evaluations and comments, in combination with results of the previous technical and dominance analyses, final designs were developed for preconceptual plugging systems.

3.3.1 Desired Plug Functions and Performance Measures

A primary function of this study is containment of hazardous waste material and its isolation from the biosphere for long periods of time. Using a criterion such as "containment of hazardous waste material" suggests that, for example, a moderate plug scheme's permeability need not necessarily be a disqualifying characteristic as long as the plug scheme does not permit migration of hazardous radionuclides. Stated differently, using such a criterion has advantages compared to a more restrictive and conservative measure (such as "flow across the plug scheme") because radionuclide absorptive, dispersive, and retentive properties of the plug schemes are taken into account. However, such a criterion complicates the analysis of the problem because measurement of radionuclide migration across a plug is quite difficult. First, typical nuclear waste material contains a multitude of radionuclides, each of which can react differently when they come in contact with plug material. This makes it extremely difficult to determine how much of each radionuclide may pass through the plug media. Second, it would be difficult to define the region of measurement and the concentration of radionuclides therein that may be considered "hazardous." Hence, even if it were possible to determine what concentration of each radionuclide passes through a particular plug scheme, it would be difficult to assess if it represents a potential hazard or not. The concentration at the end of the plug is presumably referenced to a wider-bounded biosphere before being compared to regulatory limits on allowable concentrations.

There are, however, numerous advantages to using the "flow through the plug scheme" as the basic plug function. It is easier to measure flow and define plug performance criteria in terms of permeability. Altogether, it would seem that a combination of "flow" and "radionuclide migration" through plugs may be a satisfactory performance measure. This is the approach adopted for the solicitation of expert judgment and it is further described below.

Hazardous waste material may gradually find a way to the biosphere either through the plug(s) or through the basalt host rock. It is conceivable that radionuclide migration through the host rock will take place at such a slow rate as to make this "failure" mode virtually impossible. Such an assumption presumes that the repository is placed at great depth and that the host rock does not have large and continuous fractures. In any case, the analysis in this study was concerned with radionuclide migration through the plug and its immediate environment.

Figure 76 illustrates a typical plug and its immediate environment. Radionuclides can potentially migrate across a plug in any one or a combination of the following three ways:

- By migration through the plug;
- By migration through the plug/rock interface; and/or
- By migration through the disturbed rock surrounding the plug.

In reality, of course, all three may contribute to total flow across the plug. To measure the flow, one can define a hypothetical "barrier" (such as that shown in Figure 76) and measure all flow across the barrier. An important difference in flows through different media is that the radionuclide absorptive properties of the media may vary. To account for these variations, one can make adjustments for each transmission media, as shown in Figure 77. This scheme is designed to combine "flow" and "radionuclide migration" criteria in a qualitative way. The scheme provides another advantage: in analyzing different plug material zones in the same plug environment, analysis of flow through disturbed rock need not be repeated.

3.3.2 Systematic Plug Evaluation Procedure

It was desirable to have an evaluation procedure that was structured and that made use of available information in a systematic way. In addition, the evaluation procedure had to recognize the limitations that exist on the quantity and quality of available information. The evaluation procedure adopted is schematically presented in Figures 78 and 79. It had the following characteristics and advantages:

- The procedure was systematic and easily documented;
- It relied on judgmental evaluation by a number of professional experts (evaluators) knowledgeable in various aspects of tunneling, plugging, material properties, and geotechnical design and construction;
- It forced the evaluators to consider the same number of pertinent parameters in evaluating each plug scheme by

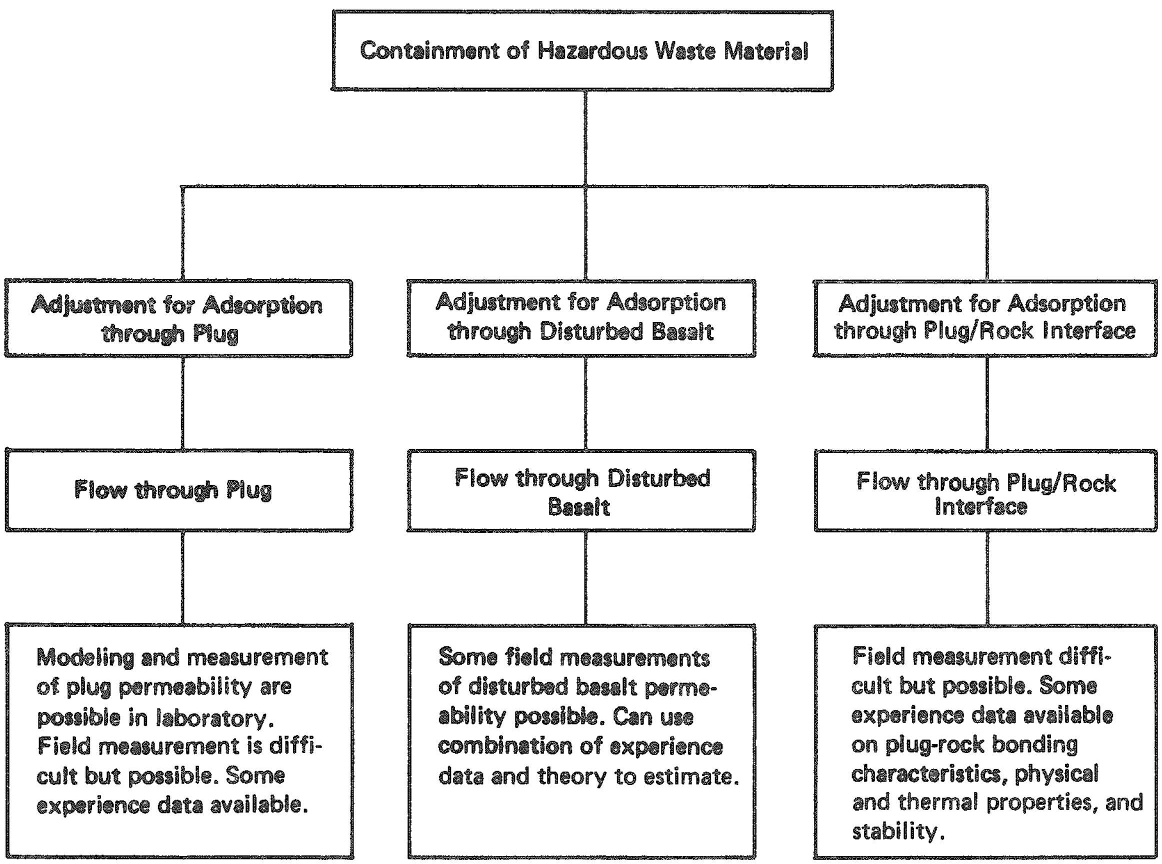


FIGURE 77

EVALUATION SCHEME BASED ON FLOW AND WITH ADJUSTMENT FOR RADIONUCLIDE MIGRATION

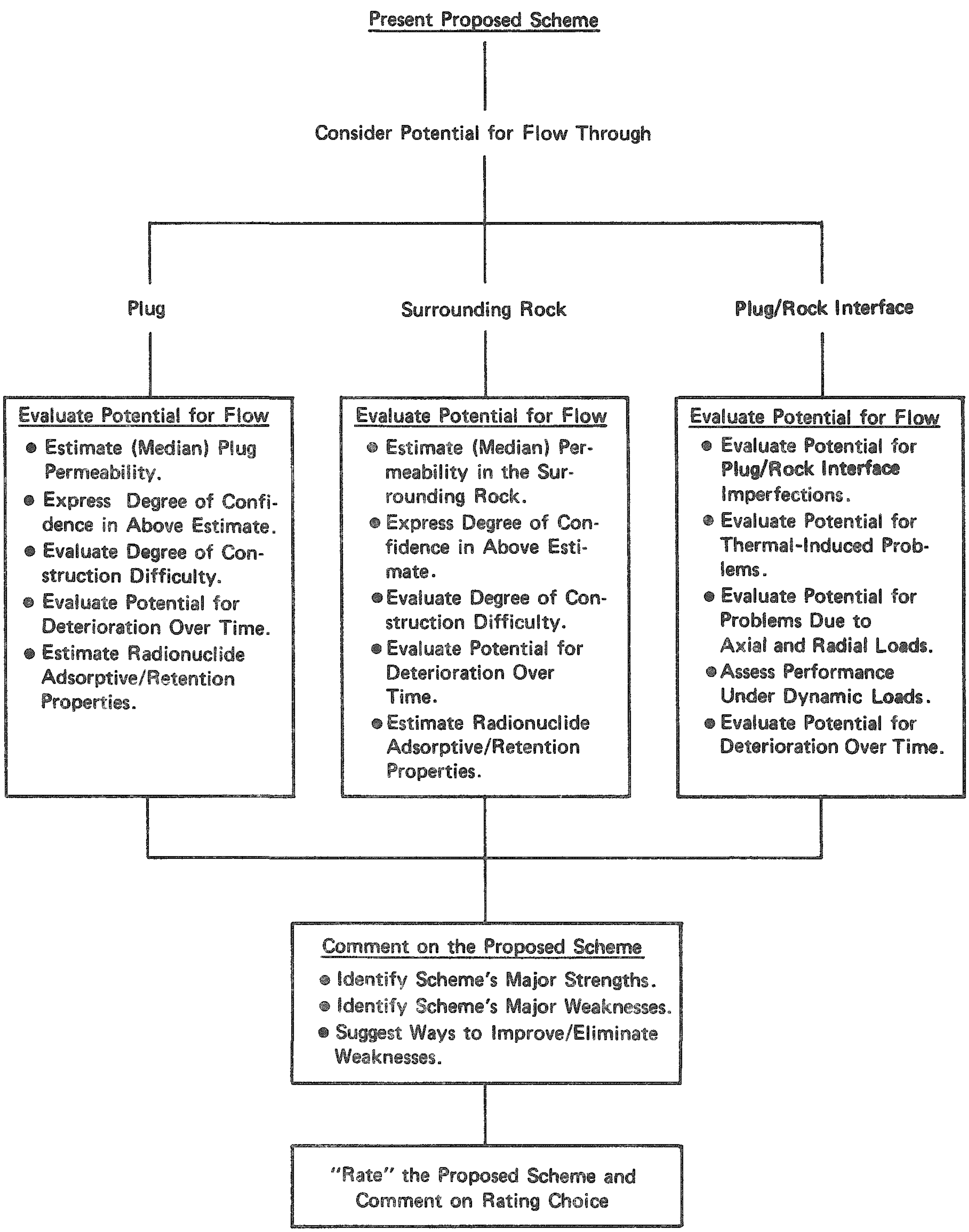


FIGURE 78

SCHEMATIC OF PLUG SCHEME EVALUATION PROCEDURE

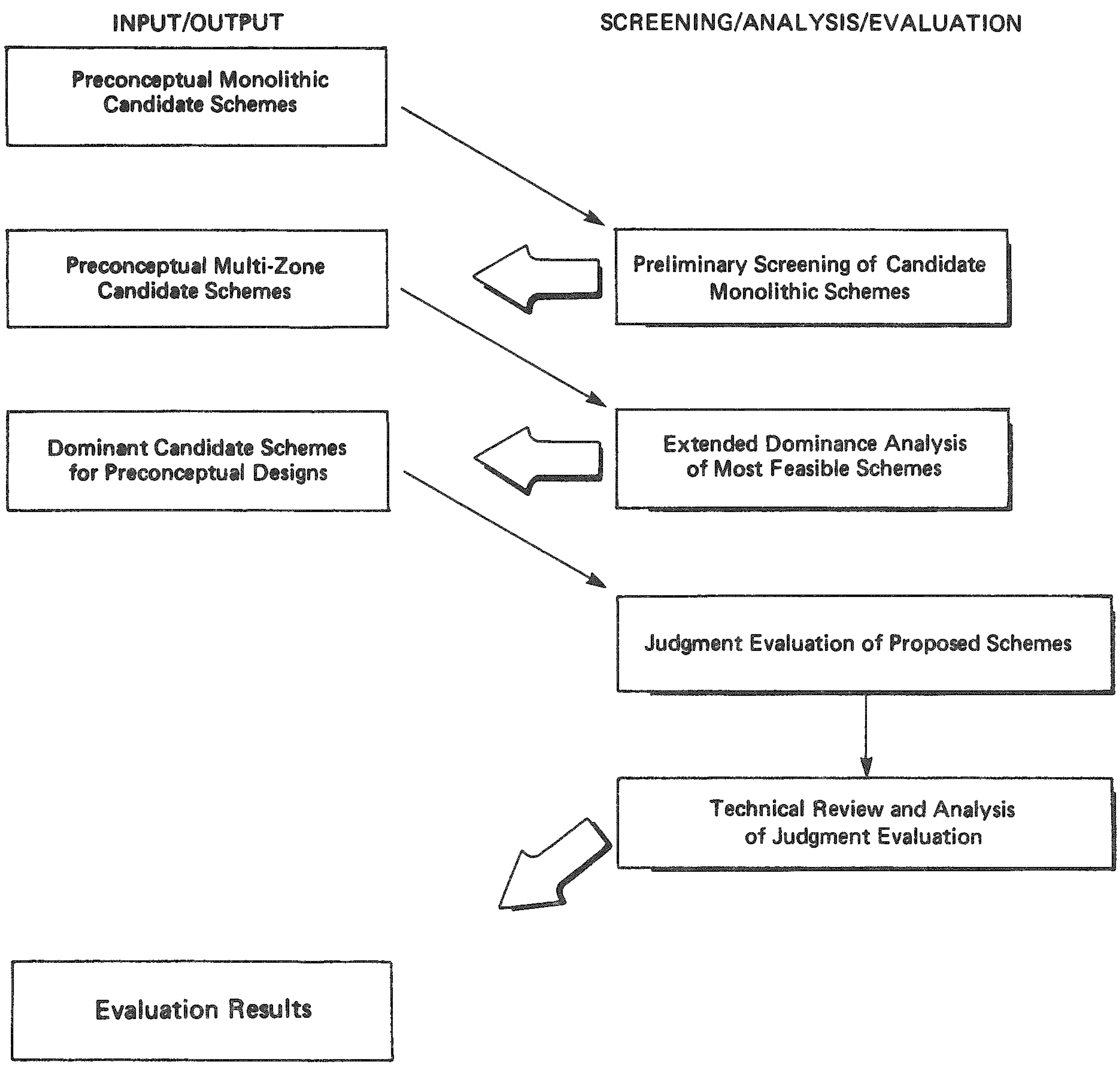


FIGURE 79

SCREENING ANALYSIS AND EVALUATION
OF CANDIDATE AND PROPOSED SCHEMES

soliciting well-focused input, hence increasing the likelihood of obtaining a thorough set of responses from each respondent for each proposed plug scheme;

- It specifically recognized the limitations in design/data at the present preconceptual stage;

- It broke down a complex system (plug scheme) into smaller sub-components and combined the assessment of these components in evaluating the whole scheme;

- The confidence level of results could be improved with additional evaluations as more information or additional evaluations became available; and

- It attempted to qualitatively capture the evaluators' views and reservations recognizing: (1) the rigid plug performance required; (2) harsh environment loading conditions present; (3) long time frame under consideration; and (4) considerable uncertainties that the above conditions would produce.

The procedure assumed and required that available pertinent data about the plug components to be evaluated would have been compiled and made available to the evaluators in the form of useful summary tables. Because the plug schemes were only conceptual at this stage and because some plug material/machines were untested or unproven, some useful information about the components was sketchy and incomplete. The suggested procedure specifically recognized this fact and allowed for the uncertainties involved or anticipated.

As shown in Figure 78, the evaluation procedure was broken down into three subcomponents:

- Evaluation of potential for flow through the plug;
- Evaluation of potential through the surrounding rock; and
- Evaluation of potential for flow through the plug/rock interface due to bonding imperfections, thermal-induced problems, axial and radial stresses, and dynamic loads.

To accomplish each plug subcomponent task, the evaluators' responses to a number of questions were required. These questions and the choice of responses are shown in Appendix G. Evaluators chose from among three responses the one that most closely reflected their views on the question posed. They could, however, decline to answer questions that went beyond their areas of expertise or that in their opinion they were unqualified to answer.

Following these responses, evaluators were requested to identify each plugging scheme's major strengths and weaknesses, suggest ways to improve/eliminate these weaknesses, or otherwise comment on the scheme. Next, they were required to "rate" each proposed scheme on a four-point scale, based on the scheme's overall merits and drawbacks, taking everything into consideration. Finally, evaluators were requested to state their reasoning behind their rating choice.

The following is a brief discussion of the questions posed in the evaluation form (Appendix G) and the reasoning behind them.

3.3.2.1 Flow Through the Plug

To evaluate flow potential through the plug (ignoring any plug/rock interface problems and permeability through the disturbed rock zone surrounding the plug), it was decided to elicit responses from the evaluators on the following five considerations. Because the evaluators could have different perspectives and backgrounds, they would not necessarily consider all the important aspects of the problem unless directed to do so by a number of suitable, well-focused questions. Hence, the purpose of the evaluation process was to set up a framework to elicit useful, objective, and judgmental responses on relevant plug parameters. The directives to the evaluators and rationale for these are:

- Estimate expected plug permeability, given the specified material/machines under field conditions. (The purpose of this question was to elicit the evaluators' judgment on the possible range of permeabilities that could be expected. The evaluators did not have to specify a specific permeability but only express a "range" of expected numbers.)

- Express level of confidence in the above response. (It is recognized that evaluators may feel quite uncertain about their responses to the previous question. It was the purpose of this question to document these uncertainties in a simple and meaningful way.)

- Express degree of construction difficulties/complexities expected. (Because many of material/machines would be novel and plugging techniques nonconventional, evaluators could have a low level of confidence about their effectiveness or might wish to give conditional responses. The purpose of this question was to elicit specific comments on practicality, effectiveness, and level of confidence in the plug placement technique/machinery proposed.)

- Express potential for time-dependent properties. (Because the plug materials would be expected to perform well over long periods of time, it was important to question the evaluators for any potential or anticipated time-dependent properties that may result in a deterioration of plug's performance over time.)

- Recognize plug material's potential for absorption and retention of radionuclides as migration takes place through plug materials.

3.3.2.2 Flow Through the Surrounding Rock

The process of tunneling and excavation could be expected to increase the permeability of the basalt surrounding the plug. The degree and extent of this disturbance would depend on the tunneling methods used, the extent of anchoring and supports provided, and the geometry and orientation of the excavations. Many of the proposed plugging schemes included cutoffs and/or pressure grouting to reduce the potential for such problems. Despite such provisions, it was expected that some flow would take place through the surrounding rock and that it must be accounted for. Questions posed under "flow through the plug" (or slight variations of them) were repeated to elicit expert judgment on flow through the disturbed rock.

3.3.2.3 Flow Through Plug/Rock Interface

Potential for flow through plug/rock interface exists and deserves due attention. Unlike the previous two sets of questions, however, plug/rock interface problems could not be as readily measured and expressed as bulk permeability. Instead, the potential causes of problems for such flows had to be addressed. These causes were tentatively grouped into five categories. Each of the following five questions was an attempt to elicit qualitative information on each subcomponent of the problem:

- Evaluate potential for imperfections in plug/rock interface bond. (Poor bonding between plug/rock interface could result from many factors, such as ineffective compaction of certain material on the top portion of horizontal tunnels or voids forming between the plug and rock wall because of wall irregularities, unsuitable plug material, and improper or faulty placement techniques.)

- Evaluate potential for thermal incompatibilities in plug/rock interface. (There could be potential for developing plug/rock voids or imperfections as a result of differential expansion and contraction coefficients of plug/rock material. This problem should be considered because parts of the underground repository may be subject to transient variations in temperature.)

- Evaluate plug properties under transient and static axial and radial loads. (Plug/rock interface problems could develop if plug material experiences large deformations under axial and/or radial loads that occur over the long-run. Some of these loads could be static and constant while others could vary over time.)

- Evaluate performance under dynamic loads. (It is conceivable that the repository could be subject to dynamic loads, such as earthquakes, tectonic movements, faulting, and so on. These loads would only be exerted over short periods of time but might be of significant magnitude. The plug and plug/rock interface should be able to withstand such loads and remain intact or possess self-healing properties. The intent of this question was to identify potential problem areas or weak points in the proposed plug scheme under dynamic loads.)

- Evaluate potential for time-dependent problems. (This is similar to other questions previously asked, except that it was pointed at potential plug/rock interface problems.)

3.3.3 Evaluate Proposed Schemes Using Professional Judgment

Following a couple of preliminary trials, which resulted in modifications in the evaluation forms and procedure, three experienced evaluators were chosen for final evaluation of the proposed schemes. The selection of the three evaluators was based on their long experience and familiarity with three different aspects of tunneling and plugging, so that each scheme could be evaluated from their respective points of view. Evaluator 1 was a heavy construction and tunneling specialist with over 35 years of field and design experience with dams and tunnels. Evaluator 2 was a civil engineering design specialist with some 40 years of design and field experience. Evaluator 3 was a geology specialist with about

25 years field and design experience. Thus, these three evaluators represent about 100 years of experience in three fields considered most pertinent to the evaluation of the proposed schemes.

The evaluators were presented with a total of 19 proposed schemes; 10 monolithic and 9 multiple-zone plug schemes. Separate meetings were held with each evaluator; hence, their expressed views were independent of one another. Each evaluator was first briefed on the purpose of the meeting and the objectives of the evaluation process. Next, each was told to consider the particular environment (e.g., deep underground repository), loading conditions (e.g., hydraulic, thermal, dynamic), and time frame of the problem (thousands of years). Each was subsequently presented with Figures 76 and 77 to help breakdown and analyze the problem. The evaluation procedure (Appendix G) was then described.

Following these preliminaries, each evaluator was presented with the proposed plug schemes, one at a time (and not in the same order with different evaluators). They were asked to study the scheme prior to filling in the evaluation form. The procedure was repeated for each scheme.

It was expected that the respondents would not always agree on anticipated performance and properties of plug components. Such disagreements could occur whether or not evaluators were equally informed about the plug schemes and whether or not they had comparable experience judgments about untried schemes. The first type of interpersonal disagreement would be reconciled by discussion between the participants; however, the second kind could arise because one evaluator may be better informed or more experienced with a particular plug component than another. In this case, the views of the more knowledgeable evaluator could be weighed more heavily. However, the assumption was made that all evaluators were equally informed about the various plug components and their expressed views were equally weighed. This assumption could be relaxed if necessary without changing the procedure.

The evaluation procedure further assumed that respondents would not disagree on any question in a major way. Such an assumption was reasonable because it was understood that any major disagreements could be resolved in subsequent discussions between evaluators.

3.3.4 Expert Judgment Evaluation and Design Selections

It was found during the evaluation process that the three evaluators were reluctant to make any response to questions dealing with overall radionuclide absorptive/retentive properties, even though they were furnished with some limited, qualitative data concerning materials performance. Therefore, their overall rating of any scheme did not consider this question. A fourth evaluator, with a background in radiochemistry, was asked to evaluate in this area, but the results did not present much additional basis for discrimination between schemes.

The responses of the three evaluators are tabulated in Appendix G. Dominance analysis could not be of any help in searching for consensus among the evaluators concerning a rating for any one scheme because their individual assessment of any scheme, whether in specific question areas or in total context, differed. In order to resolve such differences in the extended dominance analysis, it would be necessary to assume some inequality of value in the judgment of the evaluators, and there was no strong basis for doing this.

A conservative approach was adopted to analyze the questionnaire results. Any scheme that received an overall rating of D by any evaluator would be considered least desirable, because the experience of that evaluator suggested some significant reservations about that scheme's feasibility or performance. Any scheme that received at least an A or B overall rating by each of the evaluators would be considered as most-preferred. It was felt that no hard distinction could be made between A and B ratings because at least one evaluator was generally reluctant to give any scheme better than a B overall rating (understandably, because every scheme is untried yet and the available data are relatively scant). On this basis, schemes were rated as shown in Table XVII. These results are in reasonably good agreement with the dominance analysis results of WCC's technical evaluations of the plug schemes.

(i) Boreholes

The cement-grout/clay-gravel slurry with bentonite pellets for boreholes matches exactly.

(ii) Tunnels

For tunnels, the evaluators preferred monolithic concrete plugs, and the next choice included concrete and basalt block. The latter choice, plus clay-sand slurry cutoff collars, was the preferred WCC choice. It is felt that long-term integrity considerations make it imperative to go with the multiple-zone concept.

TABLE XVII

JUDGMENTAL EVALUATION OF CANDIDATE MONOLITHIC AND MULTIPLE-ZONE PLUGS BY PROFESSIONALS

	Boreholes	Tunnels	Shafts
"Most Preferred" Schemes	1,3	7	15
"Second Most Preferred" Schemes	2,5	8,10	13,14
"Least Preferred" Schemes	4	6,9,11,12	16,17

REFERENCE KEY

Scheme No.	Reference Figure	General Plug Desciption
1	9	Cement grout
2	11	Clay-gravel slurry
3	10	Clay-gravel slurry with bentonite pellets
4	25a	Cement grout/melt-in-place metal
5	25b	Cement grout/compacted metal pellets
6	20, 23	Compacted earth
7	22	Concrete
8	21	Basalt block masonry
9	28a	Compacted earth/bentonite blocks/basalt blocks/ concrete
10	28b	Concrete/basalt blocks
11	29b	Compacted earth core/clay-slurry or bentonite blocks cutoff collars
12	29b	Concrete/clay-slurry or cement cutoff collars
13	16	Compacted earth
14	17, 18	Concrete
15	26a	Concrete/bentonite blocks or basalt blocks Cutoff collars
16	26b	Compacted earth
17	27	Compacted earth/basalt cutoff collars

The construction specialist evaluator had some detailed comments on how the cutoff collars might be constructed, and his concerns indicated that some careful thought will have to be given to final design of this feature. Generally, he discussed excavating and filling each collar in segments. The WCC staff felt this concept was necessary for shafts but considered that natural arching would allow a single excavation and a single backfilling operation for tunnel cutoff collars without causing excessive, additional disturbance of the tunnel wall rock.

(iii) Shafts

For shafts, the evaluators considered a multiple-zone plug of concrete with a compressed bentonite block or basalt block cutoff collar as the most preferable scheme. Monolithic plugs of compacted earth or concrete were their next choice. The WCC technical ratings favored a multiple-zone plug of compacted earth with a concrete collar cutoff. This was based on concern for increasing the disturbance effects in the shaft borehole wall if the cutoff collar were built of compressible material (e.g., the bentonite blocks) so there was some reluctance to adopt such a design, and the basalt block cutoff collar was more acceptable for this reason. On the other hand, there was some concern with the long-term integrity of that design because a major structural component, the concrete in the shaft proper, does not have the best rating for this design function. The mortar for the basalt blocks could also be a further long-term integrity problem as discussed for tunnels. On the basis of long-term integrity performance, therefore, there seems to be less risk with taking the compacted earth with concrete collar cutoff preferred by the project staff.

4 PRECONCEPTUAL PLUGGING SYSTEMS

From an analysis and evaluation of the preconceptual plugging schemes by WCC and by specialists who have many years' experience and familiarity in different aspects of tunneling and plugging, a series of recommendations pertaining to plug design have been developed. These recommendations were geared towards practical, available plugging schemes that could be expected to satisfactorily perform five functions: (1) core barrier performance; (2) plug/rock interface performance; (3) disturbed rock zone cutoff performance; (4) mechanical stability performance; and (5) long-term stability. Based on a consensus of these plug design recommendations, preconceptual plugging systems for tunnels, shafts, and boreholes have been developed.

Although the analyses provided some insight into the order of magnitude required for various plug design parameters, the analyses were limited by the quantity and quality of data available and by the simplicity of the models that were used. More detailed analyses will require sophisticated models that can be utilized and revised during the course of repository excavation, backfilling, and sealing; the input for these models will initially consist of available field and laboratory test data and assumed values. Confirming or revising the available data and the assumed values will require timely installation and extensive use of instrumentation to monitor: (1) basalt behavior during the excavation of tunnels and shafts, as well as during the waste storage period; (2) quality of plug materials and placement procedures; and (3) plug performance. Consequently, plugging system designs must incorporate not only plug materials and placement techniques but also instrumentation to monitor plug conditions and exercise quality control.

4.1 MACHINES AND MATERIALS

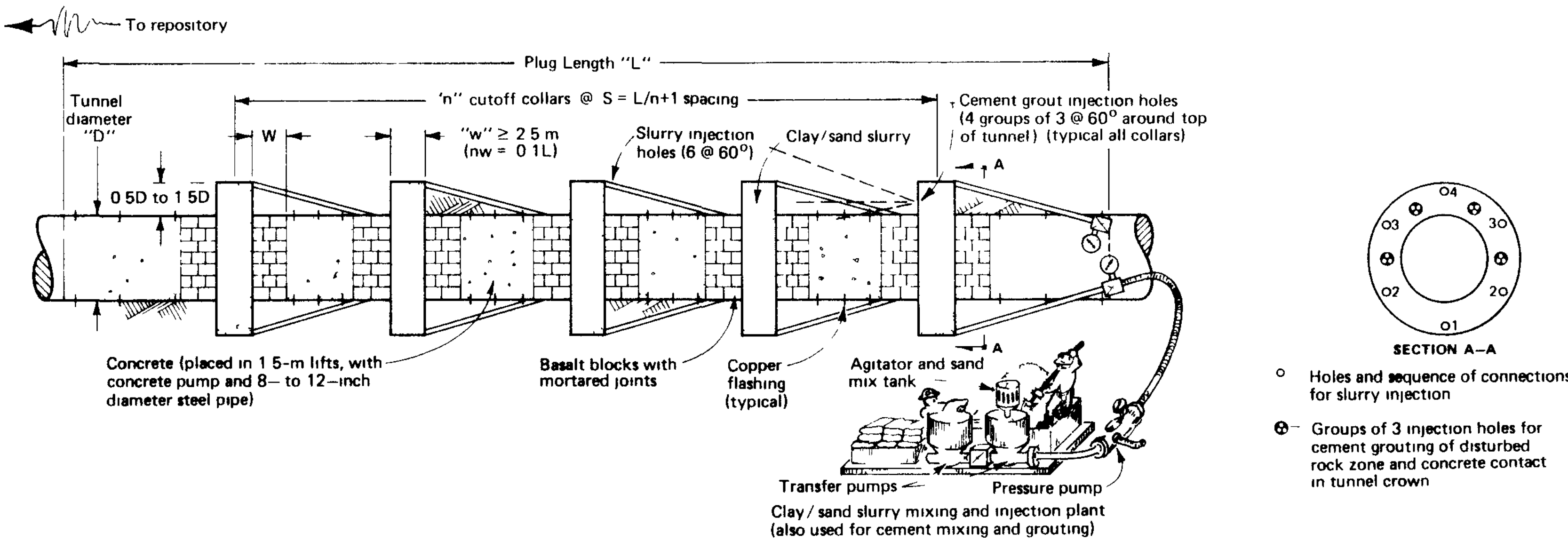
In order to combine the plugging schemes that were identified as currently possible (Chapter 2.0) with the materials and designs recommended in Chapter 3.0, the most effective preconceptual plugging systems will consist of multiple-zoned plugs. Each plug zone will be designed to perform one or more of the key design functions (i.e., core-barrier performance, plug/rock interface performance, disturbed rock zone cutoff performance, mechanical stability performance, and long-term stability) that apply to the given plug environment (i.e., tunnels, shafts, or boreholes). A discussion of the preconceptual plugging systems designed for each of the three plug environments follows.

4.1.1 Tunnels

As shown in Figure 80, this design incorporates the following features:

- Concrete with copper flashing to satisfy the requirements of core barrier, plug/rock interface, and support performance. The concrete would be placed in 1.5-m lifts using a concrete pump and 200- to 305-mm diameter steel pipe. The upper flashing would be installed in the basalt just prior to concrete placement.

- Basalt blocks with mortared joints to satisfy the requirements of support performance and long-term stability. The blocks would be hand-masoned with cement



CONCRETE FOR HIGH TEMPERATURE LOCATION T > 100°C

Mix Design per m3	
Portland Type V	289 kg
Silica flour	156 kg
Glaciofluvial sand	709 kg
¾ in gravel	1 063 kg
Water	179 ℓ
Plastiment	612 m ℓ
Concrete Properties	
Unit weight	2453 kg/m3
Porosity	14 8 %
Slump	10 8 cm
33 days strength	42 MPa
Permeability	> 2 x 10 9 cm/sec

BASALT BLOCKS WITH MORTARED JOINTS

Basalt Blocks	
Size	0 2m x 0 2m x 0 1m
Weight	10 kg
Porosity	1 24 %
strength	300 MPa
Permeability	10 9 cm/sec

Mortar

Portland Type V to Lassenite
To Glaciofluvial sand
Ratio 5 1 10
Water cement ratio 0 45
Strength 57 MPa
Permeability < 4 x 10 9 cm/sec

CLAY SAND SLURRY

Mix Design per m3	
Shurgel	56 kg
Glaciofluvial sand	483 kg
Water	804 ℓ
Unit weight	1 340 kg/m3
Porosity	80 %
Permeability	future testing

CONCRETE FOR LOW TEMPERATURE LOCATION T ≤ 100°C

Mix Design per m3	
Portland Type V	273 kg
Lassenite	55 kg
Glaciofluvial sand	755 kg
¾ in gravel	1132 kg
Water	174 ℓ
Plastiment	689 m ℓ
Concrete Properties	
Unit weight	2 481 kg/m3
Porosity	13 3 %
Slump	8 3 cm
25 days strength	36 5 MPa
Permeability	<4 x 10 9 cm/sec

FIGURE 80
PRECONCEPTUAL DESIGN OF TUNNEL PLUGS

mortar tentatively selected at this point, although ground-basalt mortar is at least recommended for future investigation. Using basalt blocks in combination with concrete is believed to provide a reasonable degree of redundancy to this design.

- Clay-sand slurry to satisfy the requirements for DRZ treatment. Cutoff collars would be excavated into the DRZ, and injection holes would be drilled so that the slurry could be pumped, under pressure, into the cutoff collars after placement of the basalt blocks (see Figure 80).

- Cement grout for treatment of DRZ and the zone of contact between the concrete plug and the tunnel crown. Injection holes will be drilled from the cutoff collar recesses and the grout would be pumped, under pressure, to seal off fractures in the DRZ as well as any gaps that exist between the concrete plug and the tunnel crown.

Preliminary calculations suggest that a plug length of 300 m may be acceptable, depending on assumptions for in-situ and disturbed rock properties, radioactive waste conditions and criteria, and other factors (as discussed in Section 3).

4.1.2 Shafts

As shown in Figure 81, this plugging system design incorporates the following features:

- Concrete to satisfy the requirements of support performance and DRZ treatment. In particular, the concrete

CONCRETE FOR LOW TEMPERATURE LOCATION T ≤ 100°C	
Mix Design per m^3	
Portland Type V	273 kg
Lassenite	55 kg
Glaciofluvial sand	755 kg
1 9 cm(3/4 inch)	1 132 kg
Water	174 ℓ
Plastiment	689 mℓ
Concrete Properties	
Unit weight	3481 kg/lm^3
Porosity	13 3 %
Slump	9 5 cm
25 days strength	36 5 MPa
Permeability	<4x10 ^{9}cm/sec

CLAY SAND MIX	
Clay	Wyoming bentonite
Sand	Glaciofluvial
Clay sand ratio	1
Max Dry density	1 983
Optimum water content	14%
Void ratio	0 45
Swell pressure	1 MPa
Estimated permeability	less than 10 ^{9} cm/s to be determined by future testing

CONCRETE FOR HIGH TEMPERATURE LOCATION T ≥ 100°C	
Mix Design per m^3	
Portland Type V	289 kg
Silica flour	156 kg
Glaciofluvial sand	709 kg
1 9 cm(3/4 inch)	1 063 kg
Water	179 ℓ
Plastiment	612 mℓ
Concrete Properties	
Unit weight	2453 kg/m^3
Porosity	14 8 %
Slump	11 cm
23 days strength	42 MPa
Permeability	<2x10 ^{9}cm/sec

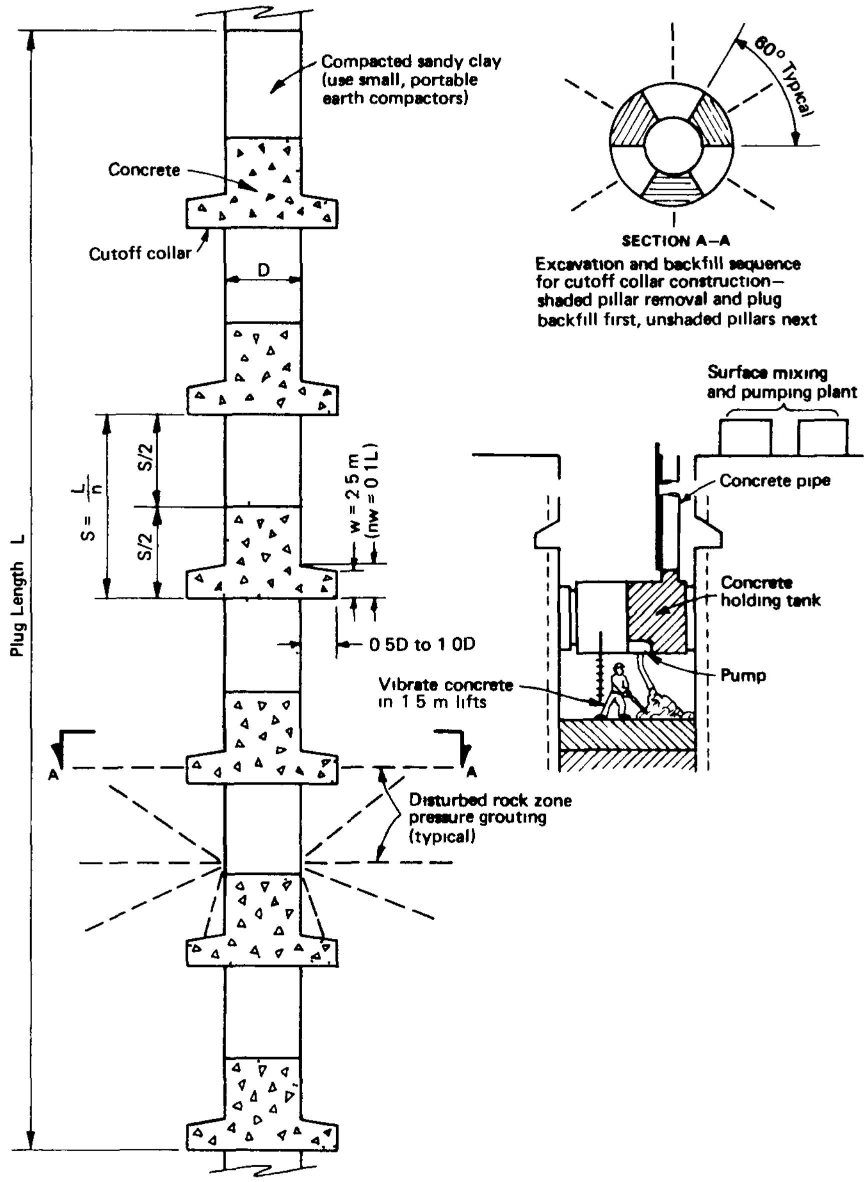


FIGURE 81
PRECONCEPTUAL DESIGN OF SHAFT PLUGS

will provide support to the DRZ during the excavation and construction of the cutoff collars, using the segmental procedure shown in Figure 81 and thereby minimizing continued disturbance of this rock zone. The concrete would be placed in lifts using a surface pump, steel pipe, and holding tank arrangement, as shown in Figure 81.

- Sandy clay to satisfy the requirements of core barrier and plug/rock interface performance, as well as long-term stability. The sandy clay would be transported and placed in lifts, using essentially the same apparatus as was used for the concrete, then compacted by a self-propelled small compactor (hand-held tampers would be used to compact near the sides of the shaft). Using the compacted sandy clay in combination with concrete would provide this design with a reasonable degree of redundancy.

- Cement grout for treatment of the DRZ and zone of contact between concrete in the cutoff collar and the top of the cutoff collar recess. Injection holes would be drilled into the sides of the shaft as well as into the sides of the cutoff collar recess (see Figure 81). The grout would be pumped, under pressure, to seal off fractures in the DRZ as well as any gaps that exist between the concrete and the cutoff collar recess.

As with the tunnel plug, preliminary calculations suggest that a plug length of 300 m may be acceptable.

4.1.3 Boreholes

As shown in Figure 82, this plugging system design incorporates the following features:

- Gravel and clay slurry with compressed bentonite pellets to satisfy the requirements of core barrier performance and long-term stability. The gravel and bentonite pellets would be mixed with clay slurry at the ground surface and pumped, under pressure, through a steel pipe. As the bentonite pellets hydrate, the mixture will swell against the sides of the borehole; also, clay within the slurry will seal off fractures along the borehole walls.

- Cement grout to satisfy the requirements of plug/wall rock interface performance and to incorporate a reasonable level of redundancy into the plug system. The grout would be pumped, under pressure, through the same steel pipe as the gravel-slurry-pellet mixture, thereby allowing for a continuous plugging operation.

As with the tunnel plug, preliminary calculations suggest that a plug length of 300 m may be acceptable. Based on the discussion and estimates in Section 3.1.5, it would require 60 days to construct such a plug, assuming a borehole diameter of 300 mm.

4.1.4 Conclusions

The materials and equipment proposed for the preconceptual plugging systems are considered practical, available, and effective combinations that can satisfactorily perform the

GROUT FOR LOW TEMPERATURE LOCATION T,< 100 C	
Mix Design per m^3	
Portland Type V	602 kg
Lassenite	241 kg
Sand	723 kg
Water	447 ℓ
W R A	1 25 ℓ
Al powder	180 g
Grout Properties	
Unit weight	2,013 kg/m^3
Porosity	33 %
Flow	16 Acc
28 days strength	29 MPa
Permeability	1×10^{-9} cm/sec

SOIL BENTONITE BACKFILL	
Mix Design per m^3	
Crushed basalt gravel	1 358 kg
Bentonite pellets	137 kg
Shurgel	31 kg
Water	436 ℓ
Initial density	1 93 gm/cm^3
Porosity	47%

Note Permeability to be determined by future testing

GROUT FOR HIGH TEMPERATURE LOCATION, T ≥ 100°C	
Mix Design per m^3	
Portland Type V	586 kg
Silica flour	315 kg
Glaciofluvial sand	772 kg
Water	414 ℓ
W R A	1 22 ℓ
Al powder	176 g
Grout Properties	
Unit weight	2 087 kg/m^3
Porosity	33 %
Flow	16 2 Acc
28 day strength	24 8 MPa
Permeability	9.6×10^{-9} cm/sec

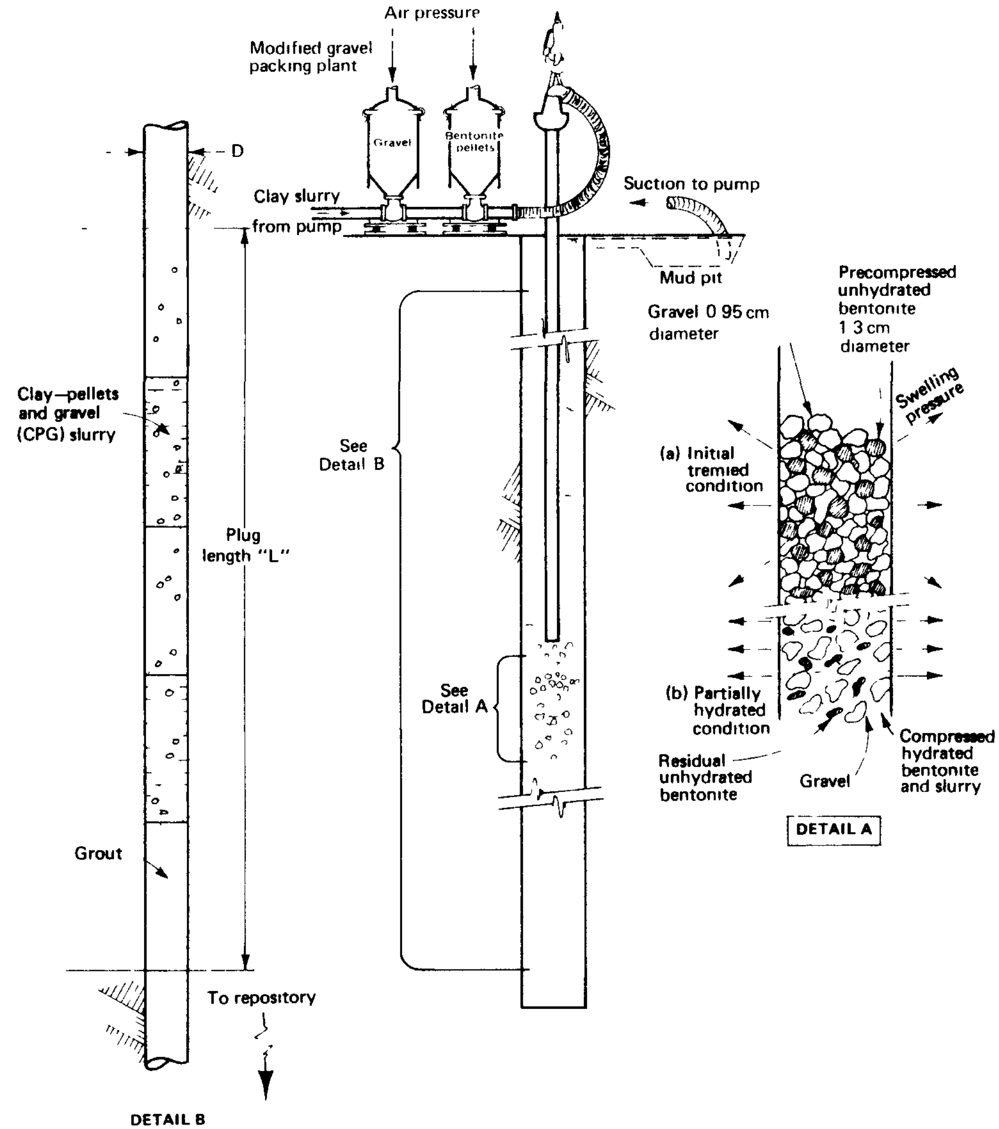


FIGURE 82

PRECONCEPTUAL DESIGN OF BOREHOLE PLUGS

required design functions. By using multiple-zone plug designs, it was possible to utilize the most desirable properties of a variety of materials and to incorporate a reasonable level of redundancy into the designs. Based on preliminary calculations, it is assumed that a plug length of 300 m would be acceptable.

4.2 INSTRUMENTATION

The final design of plugging systems will necessarily have to be a flexible, dynamic process in which design parameters are constantly reviewed, revised, and updated. Confirming or revising available data and acquiring additional data will require timely installation and extensive use of instrumentation to monitor: (1) basalt behavior during the excavation of tunnels and shafts and during the period of waste storage; (2) quality of plug materials and placement procedures; and (3) plug performance. In order for such an instrumentation system to provide the maximum information, it should provide data that can be input directly into sophisticated plug models, such as discussed in Section 3.1.2.2.

It is beyond the scope of this report to discuss an extensive instrumentation system such as contemplated for the final design of plugging systems. At this stage of plugging system development, however, it is worthwhile to consider available or potentially modified instrumentation that could be used to monitor plug quality and plug performance. Monitoring during plug placement and for some time period afterward will be required to demonstrate and document the quality and at least the early performance of the plug. The monitoring phases that are contemplated are as follows:

Phase	Time Period
Quality assurance	During plug placement
In-situ properties	During and immediately following plug placement
Intermediate performance	Up to approximately 30 to 100 years after plug placement

Quality assurance monitoring generally includes those rapid field test procedures that are conventional in earth dam or mass concrete construction; the purpose of quality assurance is to verify and document basic physical properties of the construction materials. Because sealing of boreholes to isolate radioactive waste is of a more sensitive nature than are major earth dams, important physical properties of the constructed plug should be monitored during the in-situ properties phase. Such tests are performed on some major civil construction projects. Finally, the intermediate performance monitoring phase would employ remote sensing instrumentation that had been embedded in a plug during construction. Monitoring by this instrumentation would be for a time period of perhaps 30 to 100 years. Such a time period, which is often the designed economic life of many civil engineering projects, comprises only a very small period when compared to the planned life for a radioactive waste repository. The limiting condition of monitoring would therefore be the life of the instrument.

Candidate instrumentation to be employed in each monitoring phase, for various plug material types (such as earth and concrete), and in separate categories of plugs (tunnels, shafts, and boreholes) is presented in Figure 83. The monitoring objectives and techniques for each monitoring phase is discussed below.

4.2.1 Quality Assurance

The quality assurance monitoring techniques listed are those generally performed on earth dams or concrete dams. Grain size analysis is done to assure that material delivered onto an earth dam for compaction is within specifications. When the material is compacted in-place at the specified compactive effort (e.g., two passes of a 100-ton pneumatic roller), it must be within a designed range of physical properties. An easy and significant physical property to measure after compaction is the field density (e.g., digging and weighing a known volume of the fill material), which is most often done for design verification. The maximum achievable field density of earth materials is typically sensitive to variations in moisture content and, therefore, this property is also commonly measured. Relative density tests are run on the fill material in a field laboratory for several moisture contents in order to determine the optimum moisture for compaction of that material. The material delivered onto the fill must then be brought to within an acceptable tolerance of the optimum moisture to achieve an acceptable relative density.

Concrete is subject to much less variation in physical properties than earth fills, and generally only a few simple index tests are performed to verify design intent when fresh concrete is deposited on a lift surface. These tests, which

		FIELD TESTING													MONITORING						
		QUALITY ASSURANCE								IN SITU PROPERTIES						INTERMEDIATE PERFORMANCE					
PLUG CATEGORY	MONITOR TECHNIQUE / PLUG MATERIAL TYPE	Grain Size Analysis (S)	Moisture Content (S)	Field Density (S)	Relative Density (S)	Slump and Air (S)	Viscosity (S)	Unit Weight (S)	Lab Testing (S)	Cone Penetrometer	Vane (S)	Plate Load (S)	Pressuremeter	Field Permeability (Casagrande Piezometers) *		Pore Pressure Cells v/w *	Earth Pressure Cells v/w *	Concrete Pressure Cells v/w *	Strain Meters v/w *	Joint Meters (or Extensometers) v/w *	Thermometer v/w *
TUNNELS	Earth	●	●	●	●				●	●	●	●	●	●		●	●		●	●	
	Concrete					●			●							●		●	●	●	●
SHAFTS	Earth	●	●	●	●				●	●	●	●	●	●		●	●		●	●	
	Concrete					●			●							●		●	●	●	●
BOREHOLES (Deep)	Clay Slurry	●					●	●	●	●	●			●			●		●	●	
	Clay Slurry and Gravel Pack	●					●	●	●			●		●			●		●	●	
	Cement Grout						●	●	●							●		●	●	●	●
	Earth (Gravel and Bentonite Pellets)	●	●									●		●		●	●		●	●	
BOREHOLES (Shallow)	Clay Slurry	●					●	●	●	●	●										
	Cement Grout						●	●	●												
	Earth	●	●							●	●			●							

(S) – Published testing standards available

* – Preconceptual design discussed

FIGURE 83

AVAILABLE TESTING AND MONITORING METHODS generally include a slump test, are basically used to verify water/cement ratio and thus the predicted strength. Air content, an indicator of durability and permeability, is also frequently tested.

Other tests are commonly conducted at the plant for storing concrete materials and mixing the concrete, including gradation tests on aggregate plus sand and on aggregate moisture content and quality tests on the cement. Finally, test cylinders, usually made of the fresh concrete placed in the works, are tested for compressive strength in a field laboratory.

These types of tests for earth and concrete have successfully provided quality assurance on a large number of major civil construction projects and would be applicable to the plugging systems proposed in this report.

4.2.2 In-Situ Properties

In-situ properties tests are most often done to acquire design data on complex foundations of major structures and only infrequently on compacted earth fills. To acquire accurate data, the tests must be carefully performed by technical personnel skilled in the particular measurement. Because of the wide range of physical properties possible for earth plugs, some in-situ tests are planned to document actual values achieved in the field. Some of these tests could be done concurrently with quality assurance testing while earth plugs were being compacted; other tests that require more time to perform, such as field permeability tests, would be done after completion of a plug.

4.2.3 Intermediate Performance

Instrumentation candidates shown for this phase of monitoring include equipment used in the field for conventional geotechnical construction and other civil projects. Instruments of this type can be embedded in the plug at various stages of plug construction; leads, cables, or tubes can be routed out of the plug and along the tunnels and shafts, or can be brought immediately to the ground surface through a vertical borehole and connected to read-out devices. The monitoring period would be limited by the service life of the embedded equipment. Similar equipment in earth and concrete dams has up to about 30 years experience and in some cases is still operative.

The potential for seepage paths through or along any tubes or cables from the plug to the read-out point must be considered. Distance for leads may vary from 1 km to 3 km. Electric vibrating wire instruments have been used in earth dams for leads of about 1 km or more in length and have had adequate signal quality. Geochemical studies suggested that aluminum can be a non-mobile and stable corrosion product in plug environments, and therefore, using aluminum conductors as leads for electric vibrating wire instruments may be feasible. Native copper deposits are also documented as being stable over long geologic periods. Consequently, hard-wiring might sufficiently meet the needs of avoiding seepage paths through the plug and yet provide means of connecting instruments to remote read-out points. Subsurface wireless transmission of signal data is a possibility but is considered only in a research and development status at present.

Long-term monitoring by instrumentation can provide some warning that the integrity of a subsurface plug is in question. In a long-term situation, there is little or no opportunity to inspect and verify instrument data, and it is important to consider possibilities for employing different types of instruments and in significant redundancy of units. Then, comprehensive depth and consistency of data may be sufficient to accept the recorded occurrence of an unforeseen condition of the plug and to have reasonable confidence in the safety of the plug based on the observed data.

4.2.4 Performance Data Needs and Instrumentation Methods

The analysis of plugging schemes (Section 3) identified and concentrated on seepage potential and its mitigation as a major area of importance in plug performance. Stress and strain response of the plug to possible thermal cycles, autogenous shrinkage or growth, geostatic loads, tectonic loads, and fluid pressure loads are of interest primarily in how the response might lead to changes in seepage potential through or around the plug. Possible monitoring techniques for the plug performance elements are discussed, but it should not be assumed that the problem of realizing a workable performance instrumentation scheme would be fully and practically achieved with the preconceptual designs proposed in this report. They are based on practical experience in conventional geotechnical works, but subsurface plugs at great depths in the borehole, shaft, and tunnel environments of a radioactive waste repository have not been instrumented and monitored before and much has to be learned about this task.

4.2.4.1 Permeability

One of the properties identified as having a major impact on the performance of any plug system is the permeability of the plug itself. Hydraulic conductivity coefficients, a measure of permeability, are difficult to monitor in the field for the desired parameter range of 10^{-8} to 10^{-9} cm/sec. It would be feasible to measure this parameter during or immediately after plug construction, while access to the plug vicinity was still possible.

One of several types of porous stone piezometer tips, connected to a nearby readout terminal by small-diameter tubing, may be employed, such as shown in Figure 84. Though a related permeability test, which is typically performed on laboratory samples, may take up to several months for the low permeability range considered here, there is a selected analytical technique, demonstrated in the data graph of Figure 85 for soil with a hydraulic coefficient of 10^{-6} to 10^{-7} cm/sec, whereby a shorter time interval of field test data might be extrapolated to determine the hydraulic conductivity coefficient.

Although the pumpable piezometer shown in Figure 84 is considered a permanent monitoring feature for many conventional hydraulic barrier structures, it becomes unfeasible to continue this technique of monitoring for conditions contemplated in this report once access to the general plug area is lost. Some of the reasons include: (1) problems of fluid friction head losses in long lines and consequent measurement insensitivity; and (2) the expected need to plug such lines long before access to the plug is lost in order to preclude seepage paths if the tubes break. Monitoring for permeability changes could possibly be continued using backup instrumentation with long-range signal transmission capability, such as by electric, vibrating-wire pore pressure cells (Figure 86). This technique is really an indirect permeability measurement. The concept would be to measure the fluid pressure head at multiple points

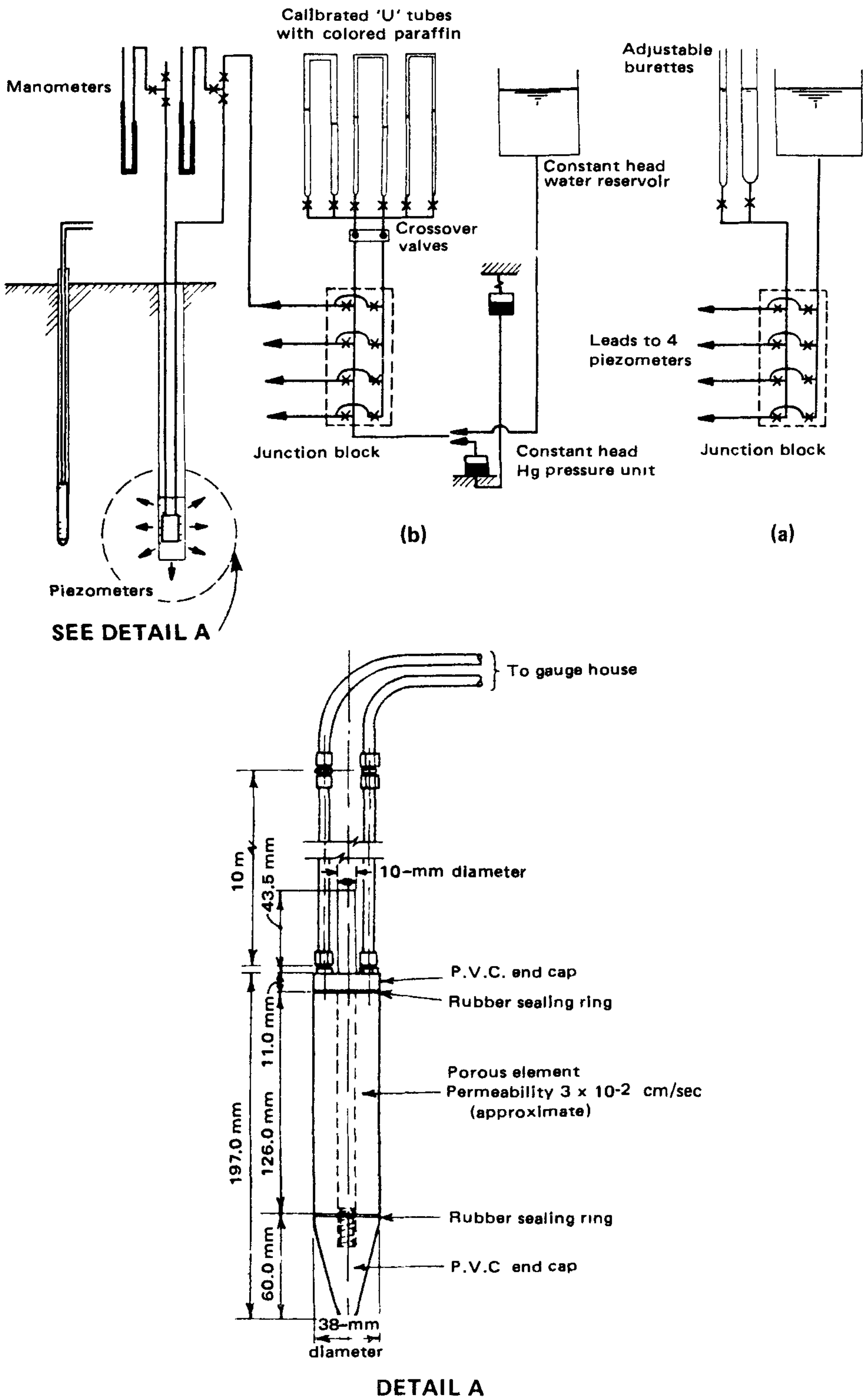


FIGURE 84

PIEZOMETER SYSTEM (PUMPABLE)

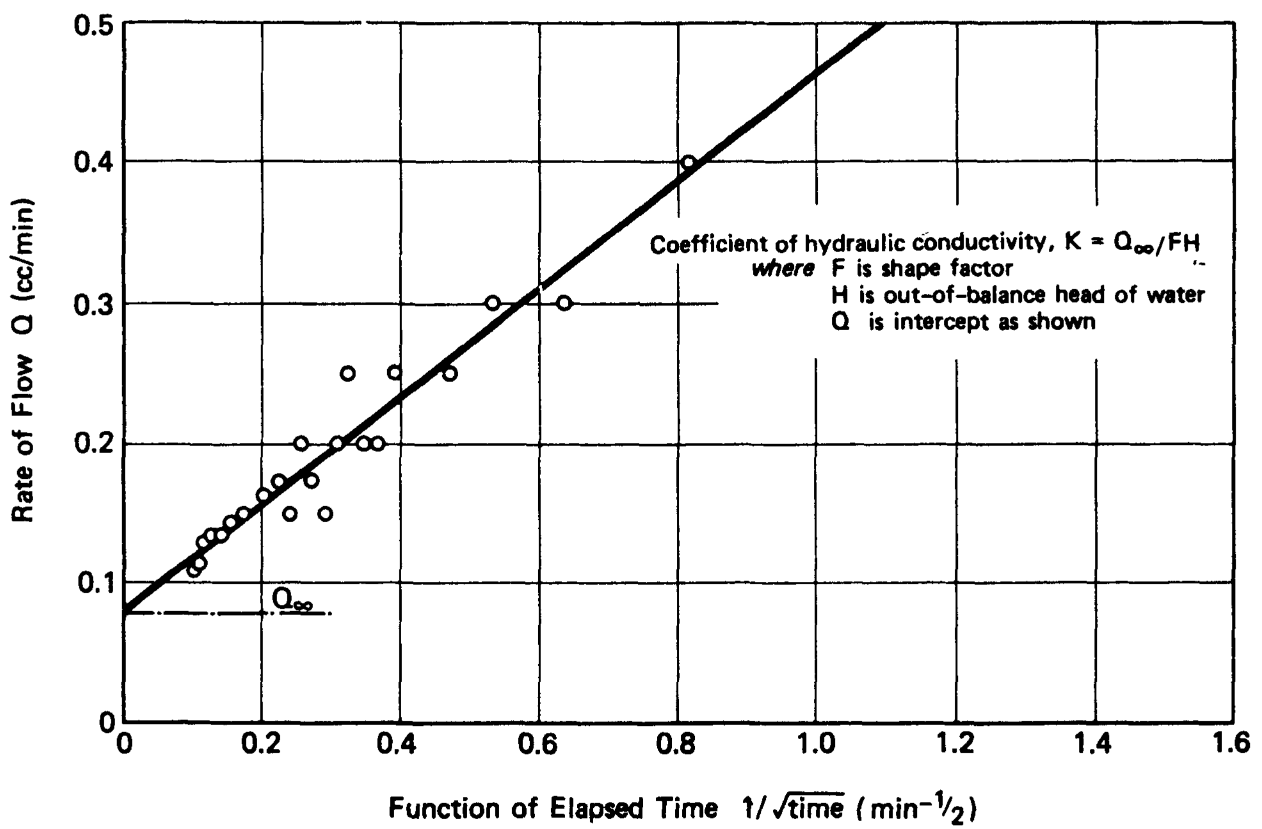


FIGURE 85

ANALYTICAL TECHNIQUE FOR PIEZOMETER PUMPING DATA IN LOW PERMEABILITY MATERIAL

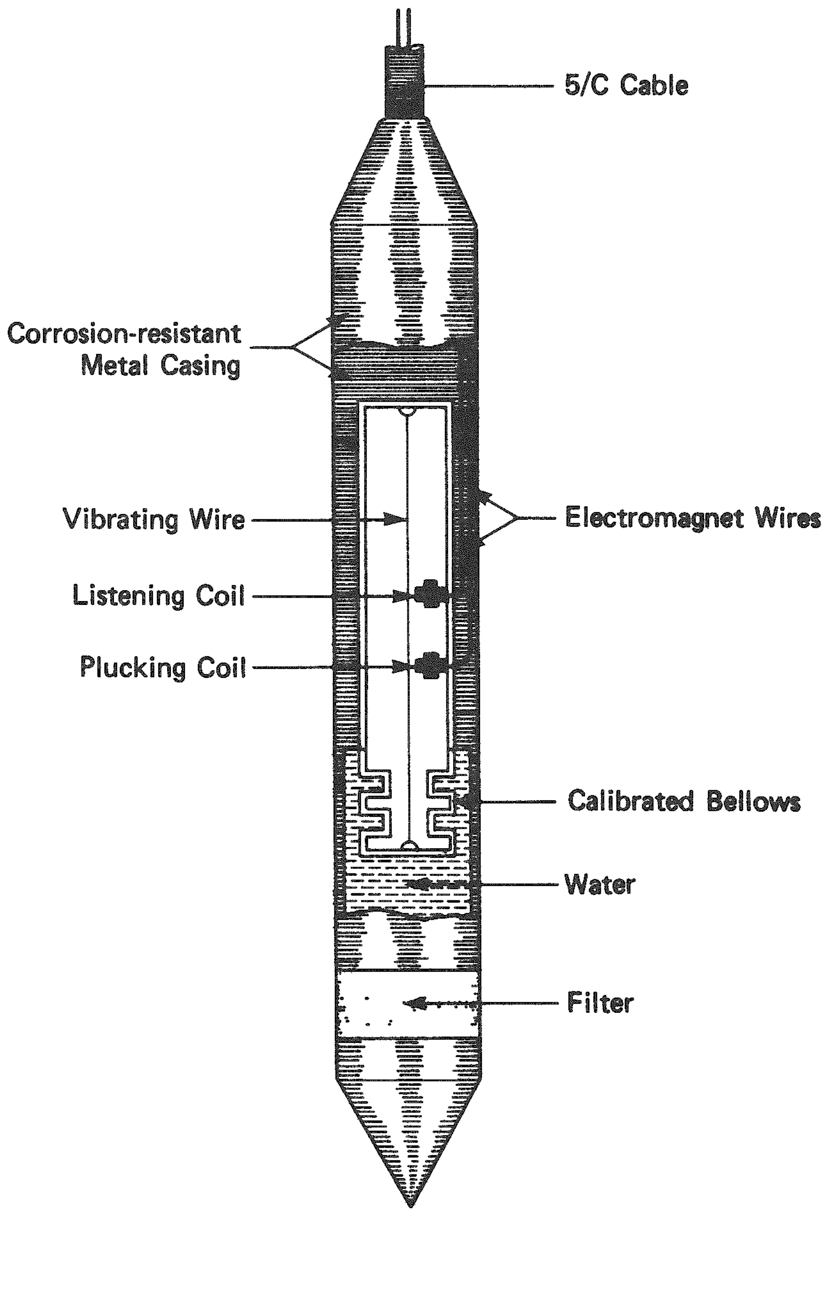


FIGURE 86

ELECTRIC, VIBRATING-WIRE PIEZOMETER

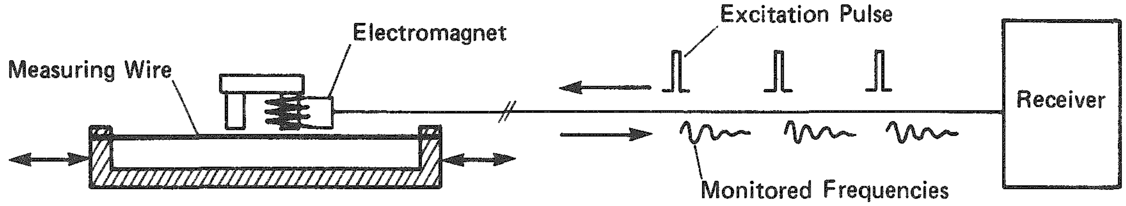
within the plug system at several sections along the plug length. Knowing the distance between monitoring points and comparing it with the differential pressure head yields the hydraulic gradient. The velocity of flow is proportional to the product of hydraulic gradient and the hydraulic conductivity coefficient. Therefore, when a 'downstream' pressure rose relative to a constant upstream pressure, it could be inferred that the hydraulic conductivity of the plug between the points has increased.

The practicality of the electric, vibrating-wire sensor is that the signal is of a digital type and may be transmitted over long distances without signal degradation and error (Figure 87). It is not absolutely certain that the insulated copper (or aluminum) conductor cable is an acceptable, permanent installation in the plug at this time, but it may be feasible.

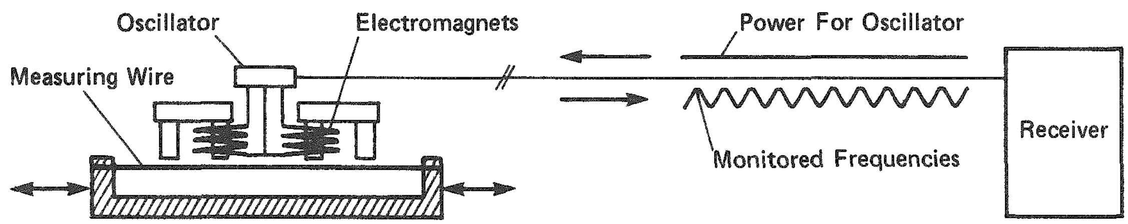
4.2.4.2 Stress/Strain

Changes in plug stresses or in interface contact pressures between a plug and a shaft or tunnel wall may signal significant changes in plug system performance. Similarly, displacements with time may precede changes in plug performance.

An engineered soil fill is usually a relatively heterogeneous construction material with significant variation of elasto-plastic, stress/strain behavior throughout its mass. In instrumentation schemes, it is common to try to average soil fill response to load (1) by using large numbers of sensors, (2) by employing stress meters with large sensor areas (Figure 88), or (3) by employing strain meters with long gage



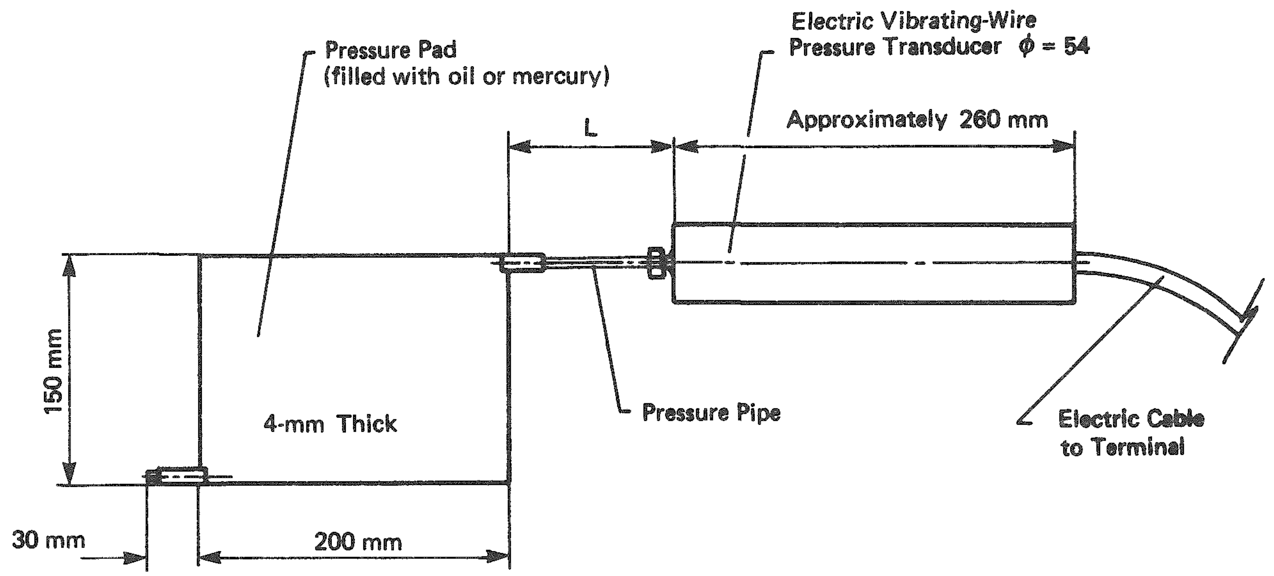
(a) Intermittently Vibrating Measuring Wire



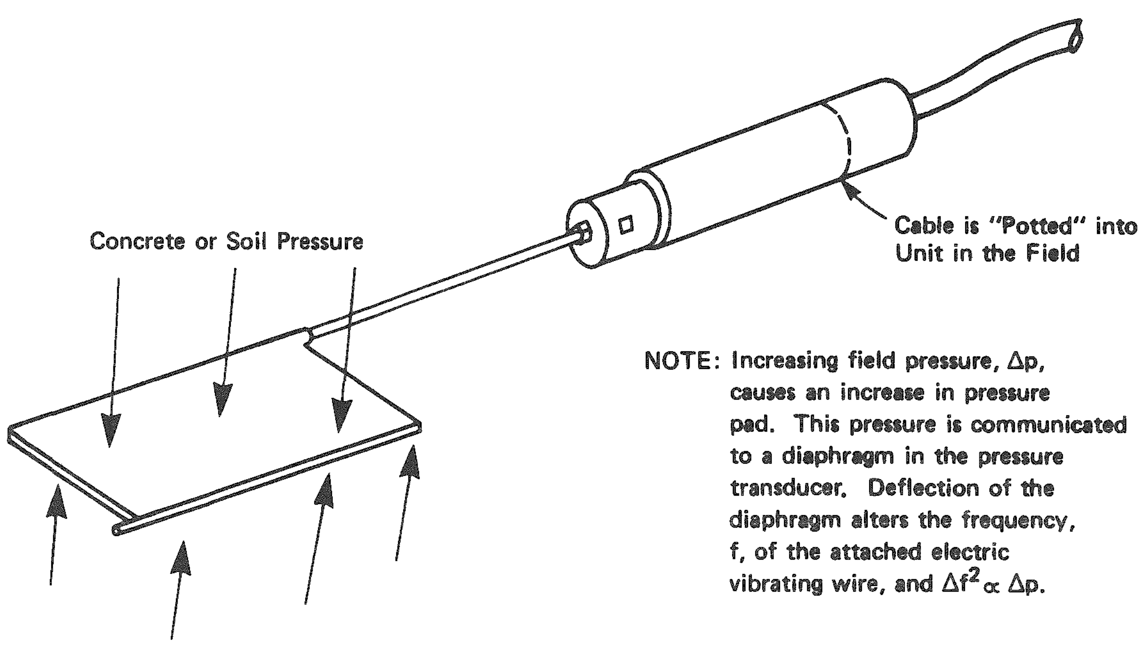
(b) Continuously Vibrating Measuring Wire

FIGURE 87

VIBRATING WIRE SENSORS, SIGNAL TRANSMISSION



(a) Plan View Details



(b) Field Arrangements

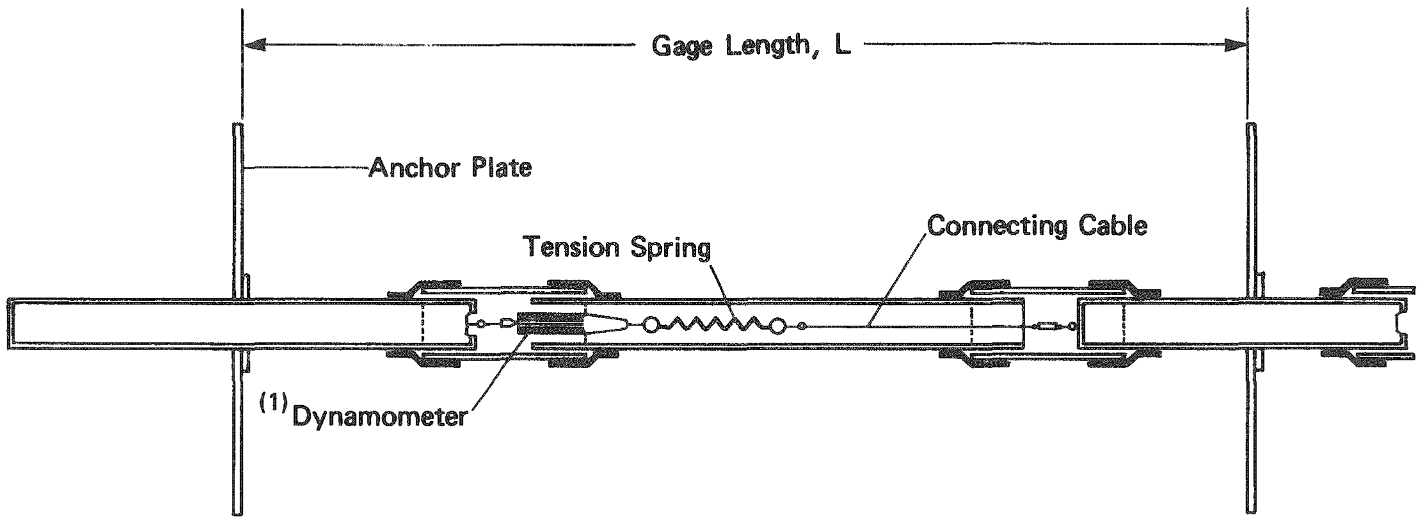
FIGURE 88

PRESSURE CELL DETAILS

lengths (Figure 89). The need for averaging load response throughout a relatively uniform and more elastic plug material, such as concrete, is less demanding but still necessary. This is true if only for reasons of possible nonuniform loading conditions.

It would be prudent to avoid instrumentation that presented relatively large, potential seepage paths parallel to a plug axis which would tend to preclude long strain gage or extensometer type apparatus parallel to the axis of the plug. This would also be true of gages oriented to monitor transverse strains or deformations in the plug, such as joint meters, which are designed to measure vertical separation between a plug and a tunnel crown (Figure 90), and which require leads to be laid out parallel to the plug axis en route to a remote terminal; similarly, stress or pressure meters.

For these reasons, intermediate performance, stress/strain instrumentation, such as pressure meters for axial measurements of load response, or pressure meters and deformation gages for transverse response, should be located in the downstream half or one-third of the plug length (i.e., the end of the plug away from the repository). Note that exceptions would be desirable for prototype testing schemes where radioactive leakage would not be a consideration, and complete stress/strain data throughout the plug would be desirable. Complete stress/strain instrumentation is available in electric, vibrating-wire type gages. When considering (1) probable terminal distance, (2) required signal strength, and (3) a demonstrated long history of use, this type of instrumentation appears to be most desirable.

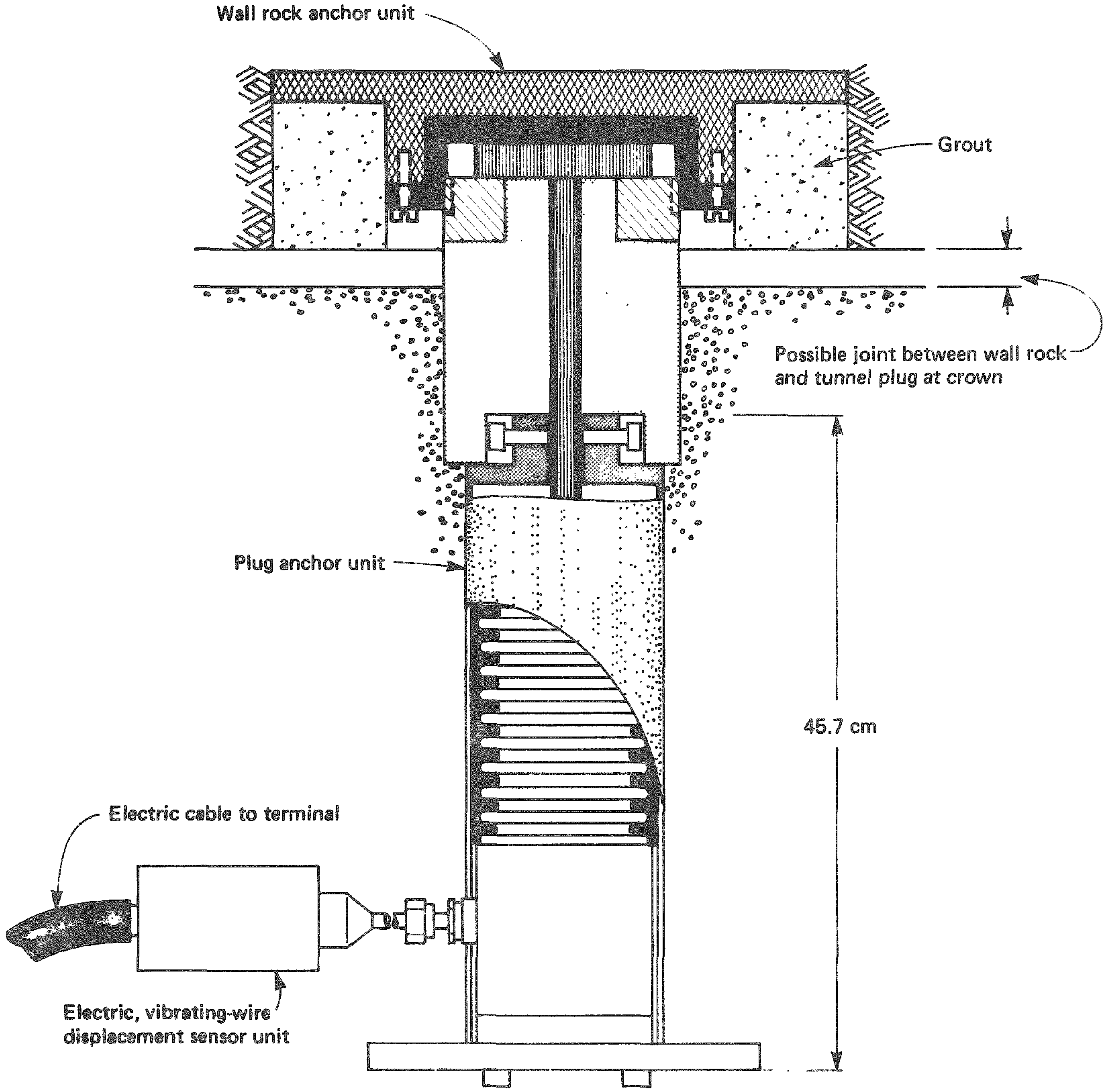


NOTE:

(1) Any ΔL causes a change in spring tension, and hence, changes force on electric, vibrating-wire dynamometer. This changes the natural frequency, f, of the vibrating wire. ΔL is proportional to Δf^2.

FIGURE 89

LONG-BASE STRAIN GAGE FOR EARTH DAMS



NOTE: The two separate anchor units may be embedded entirely within the plug for functioning as an internal strain gage.

FIGURE 90

ELECTRIC VIBRATING WIRE JOINT METER

4.2.4.3 Temperature

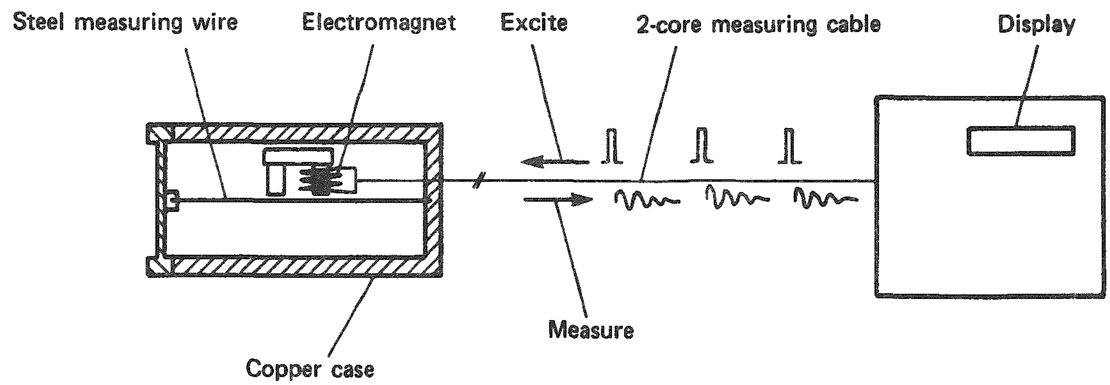
Electric, vibrating-wire thermometers are available and are shown in principle in Figure 91. However, the maximum standard range is 70°C. Maximum plug temperatures might be finally specified somewhere in the range of 50°C to 100°C, and so available thermometers may or may not be capable.

4.2.4.4 Other Transducer Types

All instrumentation, even that for the major civil works like dams and tunnels, is in a rapid state of flux. On some projects, the decision on all of the transducer types to be employed to monitor performance is delayed until the actual time for installation arrives. The philosophy is to be able to benefit by any late developments in the technology. Nevertheless, it is a poor philosophy to depend entirely on newly developed instrumentation. At least 5 or 10 years actual field experience is probably needed to identify problem areas in any new instrumentation. For that reason, a major, or at least significant part of the monitoring scheme, should depend on instrumentation with at least this much proven experience and preferably about 15 or 20 years experience.

4.2.5 Preconceptual Design of Instrumentation Schemes

The intent of the present preconceptual design is to include basic instrument types that seem feasible at this time, that have good field experience records in related work, and that have some level of acceptance in engineering practice. Preconceptual designs to monitor data relevant to evaluating selected elements of performance for various plugs, including boreholes, shafts, and tunnels, are shown in Figure 92.



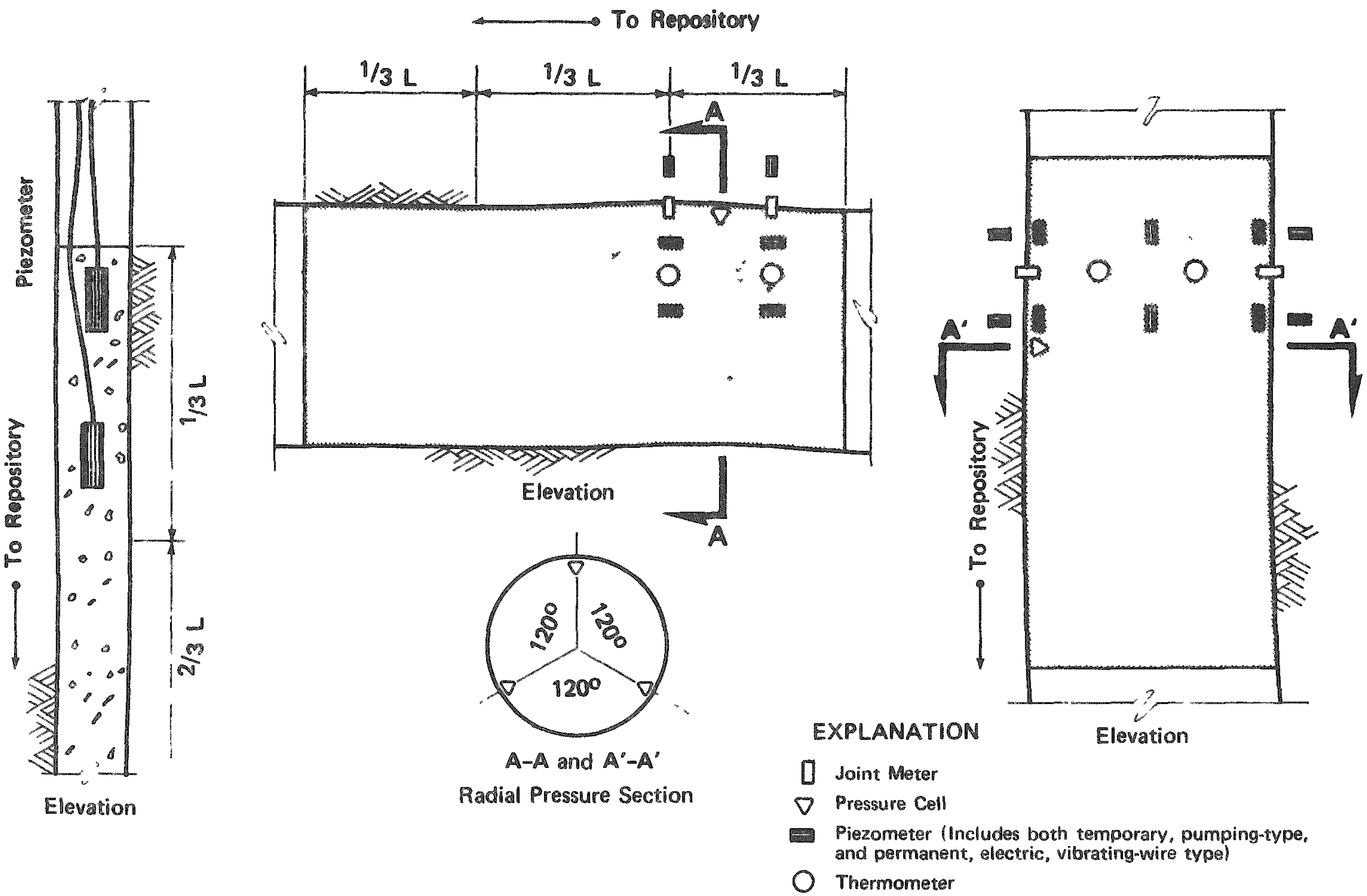
NOTES: Temperature change produces different length changes in vibrating-wire and its outer case, causing natural frequency of the tensioned wire to change.

$\Delta T = K\Delta f^2$

Standard maximum range is 70°C. Somewhat higher range may be possible, but requires special design.

FIGURE 91

PRINCIPLE OF ELECTRIC, VIBRATING WIRE THERMOMETER



(a) Boreholes (b) Tunnels (c) Shafts

FIGURE 92
PRECONCEPTUAL DESIGNS OF PLUG INSTRUMENTATION

4.2.6 Conclusions

Quality assurance and some in-situ properties equipment and techniques are covered adequately by relevant published standards, such as American Society for Testing and Materials and American Society of State Highway Officials standards. Some in-situ properties and most intermediate performance instrumentation are generally state-of-the-art, non-standard apparatus. Electric, vibrating-wire instrumentation appears to be the most feasible means currently available for monitoring intermediate plug performance when the following factors are considered: (1) probable long-term strength, (2) demonstrated long history of use, and (3) the possibility that these sensors could be used with copper or aluminum leads that would be stable in the expected plug environment.

5 LIMITATIONS OF THE PRESENT STUDY

The present study was limited in purpose and scope because of uncertainties about many key design parameters and because of a general lack of specific requirements for the overall waste isolation program. Because many of the key design parameters (e.g., approximate layout of the repository, its geometry, site-specific parameters and conditions, etc.) were not specified, it was not possible to carry out a thorough numerical or probabilistic analysis within the scope of this preconceptual study. More specifically, by being restricted to the use of simplified models, it was difficult to distinguish clearly between alternative plugging schemes, other than to make some general order-of-magnitude-type comments.

Many of the data used in the preliminary numerical and probabilistic analyses were only approximately defined or were based on limited ranges of values resulting from a specific sequence of events or loading conditions. Some of these "scenarios" were only implicitly assumed (i.e., not explicitly stated) and other scenarios having different data ranges and values might be conceptualized by other informed experts in their respective fields. Despite such limitations, these analyses provide helpful insights into the relative merits and drawbacks of alternative plug schemes analyzed under similar or identical loading conditions. Hence, the results were "instructive" and constitute a valid basis on which to screen the preconceptual plug schemes and to arrive at first approximations of suitable plug designs.

Within the constraints of these limitations, the present study also provides order-of-magnitude-type estimates for plug system performance criteria that can be achieved with present technology in the immediate plug environment, under certain plausible loading conditions. As such, the results presented in this report can form the basis for further, more sophisticated model studies and field studies of plug system design and performance criteria.

6 SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

6.1 CANDIDATE SCHEMES

Candidate schemes were assembled on matrices, with a separate matrix provided for each plug environment, i.e., boreholes, shafts, and tunnels. Each matrix listed all the candidate plug materials and plug placement machinery preferred for use in a specific environment.

The relative availability of a machine and a confidence level that a machine and material combination could be successful in plugging the specific environment comprised the basic evaluation criteria. The first evaluation was subjective and generally incorporated engineering judgment of three individuals (two engineers and one geologist) who have about 55 years combined design and construction experience. The candidate schemes are rated at this time as: (1) most feasible schemes; (2) schemes considered possible at this time with little or no modification; and (3) unproven schemes that would require extensive modification of existing equipment or design and demonstration of new equipment. Reservations about the degree of confidence in individual cases were experienced at almost every level of review, but the overall evaluation was considered an acceptable result for preconceptual purposes.

6.2 TECHNICAL ANALYSES

Both numerical and probabilistic analyses were carried out to provide order-of-magnitude estimates of: (1) the magnitude of some of the predictable environment changes expected to have major impact on the performance of a plug; and (2) the relative efficiency of various design concepts that may enable the plug to perform well in the predicted environment.

Only thermomechanical and hydraulic performances of the plug and its environment were felt to be useful for any prediction at this stage of the preconceptual study. The related numerical analyses were based on idealized models and employed closed-form solutions. The probabilistic analyses used empirical models developed from probabilistic assessments of engineering judgment based on published research and experience. A computer was used to develop models, extract random data samples, and develop data for the probability analyses of plug and wall rock performance. Compatible prediction results were noted from the two analyses techniques. Generalized results of the analyses are as follows:

(1) The superimposed stress on a rigid plug in basalt, (e.g., concrete) due to a 50°C temperature rise may be 28.5 MPa, which is about equivalent to the existing overburden pressure. This level of stress is significant, e.g., equal to compressive strength of a moderately strong concrete. Additionally, shear stresses along the plug/rock interface due to differential axial strain may approach 11 MPa, which is more than twice the expected bond strength of concrete. These shear stresses can be significantly reduced if axial movement is restrained.

(2) A parametric study of the influence of a disturbed rock zone that may develop as a result of any large diameter (e.g., 7 m) horizontal excavation in basalt shows that: (1) the depth of the disturbed zone

produced by drilling and blasting may be several orders of diameter; and (2) in such cases and without cutoff collars, the plug may need to be several kilometers in length in order to limit seepage to 1 m^3/year. The numerical study fixed the disturbed rock permeability at a uniform 10^{-7} cm/sec and varied the diameter of the disturbed rock zone.

(3) Probability assessments were used to develop a model of the disturbed rock zone showing probability distributions for the diameter of the disturbed rock zone and the variation of increased permeability from the wall rock surface back to the outer limit of disturbed rock. The assessment suggests an exponential variation of the hydraulic conductivity coefficient.

(4) The probability model shows an extreme sensitivity of plug length to the assessment of the disturbed rock zone diameter and changed permeability. Plug lengths necessary to give a high probability of limiting seepage to 1 m^3/year are on the order of tens of kilometers.

(5) If the inner tunnel plug were constructed to a 10^{-8} or 10^{-9} cm/sec permeability, almost all of the seepage would be concentrated in the surrounding disturbed rock zone. Both numerical and probabilistic models show the importance of dealing with this disturbed rock zone.

(6) Noting that the most probable values for the hydraulic conductivity coefficient at the wall rock surface are

between 10^{-4} and 10^{-6} cm/sec (for controlled drilling and blasting excavation methods), the benefit of correcting permeability in the disturbed zone to no worse than 10^{-6} cm/sec by grouting was investigated using the probabilistic model. Required plug lengths were now less than 10 km for a high probability of limiting seepage to 1 m^3/year. Because the ability to achieve those results by grouting are uncertain, and the required plug length is still very long, the grout treatment technique is not too attractive. The difficulty of correcting the seepage path through a disturbed rock zone points up the desirability of minimizing such a zone by careful consideration of the excavation method, presently favoring a bored circular tunnel with immediate roof support behind the boring machine (and in conjunction with any excavation technique). Tunnel supports and spiling may be required, regardless of excavating techniques, to prevent changes in wall rock permeability.

(7) The benefit of incorporating cutoff collars around a plug to intersect flow in the disturbed rock zone were investigated. This technique involves excavating the disturbed rock zone over a length of tunnel sufficiently short to promote overburden load transfer (arching) to adjacent rock or temporary tunnel supports without further relaxation above the fresh excavation. It appears this may be a very effective technique and may permit plug lengths to tens of meters if cutoff collars of a hydraulic conductivity coefficient 10^{-8} cm/sec can be successfully placed.

(8) Numerical analysis of the minimum plug length required to limit radionuclide concentrations at the downstream end of the plug showed that of the radionuclides chosen for analysis on the basis of half-life, Iodine 129 would require the longest plug. If a plug consisted of non-absorptive (retardation coefficient = 1) and relatively permeable (hydraulic conductivity coefficient 10^{-7} cm/sec) material, a plug length on the order of 16 km would be required. If a plug material of similar permeability, but significantly greater absorptive capacity (R = 100), were used, the required plug length is then less than 200 m.

(9) A heavy construction consulting and engineering firm evaluated the preconceptual plugging schemes and concluded that three schemes, all involving melt-in-place metal plugs, were not feasible. Industry sources reported that past experience shows damage to rock at the temperatures involved.

6.3 DOMINANCE ANALYSIS

Dominance is one of the fundamental concepts of decision analysis. Simply stated, an alternative "A" is said to dominate alternative "B" if it can be shown that alternative A is at least as desirable as alternative B with respect to all evaluation measures and is strictly more desirable with respect to at least one measure. The object of dominance analysis for comparing plug schemes was to identify those schemes that were dominated by one or more others because the dominated schemes would never be ranked highest using any evaluation technique. To this end, numerical ratings were developed for five plug design functions: (1) core barrier performance; (2) plug/rock interface performance; (3) support performance; (4) disturbed rock zone performance; and (5) long-term integrity. Rating matrices were developed such that each of the appropriate preconceptual plug schemes were rated with respect to each appropriate design function pertaining to tunnels, shafts, or boreholes. The completed rating matrices were then used as the basis for the dominance analysis and the implications of this analysis were as follows:

(1) Tunnels - A plug consisting of concrete is considered most appropriate based on core barrier performance, plug/rock interface performance, and support performance. Clay/sand/silt slurry mixtures are considered appropriate for disturbed rock zone treatment and long-term stability, but basalt blocks with cement-mortared joints are considered more appropriate for long-term stability.

(2) Shafts - Compacted earth plugs rated high for core barrier performance and plug/rock interface performance, and moderately high for long-term integrity. Concrete is considered most appropriate for support performance and is preferred for disturbed rock zone treatment because it can provide support when constructing cutoff collars.

(3) Boreholes - Gravel and clay slurry with bentonite pellets rated among the highest in core barrier performance and long-term integrity, while cement grout is dominant in plug/rock interface performance.

6.4 EXPERT EVALUATION AND JUDGMENT

In order to broaden the base of engineering judgment used in evaluating the preconceptual plugging schemes, it was necessary to solicit the opinions of specialists who are knowledgeable in various aspects of tunneling, plugging, material properties, and geotechnical design and construction. Three evaluators were chosen: (1) a heavy construction and tunneling specialist who has over 35 years of field and design experience with dams and tunnels; (2) a civil engineering design specialist who has some 40 years of design and field experience; and (3) a geologist who has some 25 years of major projects in field and design experience. The evaluation format consisted of multiple choice questions in which the experts were directed to evaluate the potential for seepage and radionuclide migration through the plug and surrounding rock. The format also requested them to identify the major strengths and weaknesses of each plugging scheme.

It was found during the evaluation process that the three expert evaluators were reluctant to make any response to questions dealing with overall radionuclide absorptive/retentive properties even though some limited qualitative data concerning materials performance was furnished to them. Therefore, their overall rating of any scheme did not consider this question. A fourth evaluator, with a background in radiochemistry, was asked to evaluate in this area, but the results did not present much additional basis for discrimination between plugging schemes. A consensus of the experts' opinions produced the following evaluation:

(1) Tunnels - The preference was for monolithic concrete plugs; the second most preferred scheme was masoned

basalt blocks or a multiple-zoned plug of basalt blocks in combination with concrete.

(2) Shafts - A multiple-zoned plug of concrete with a compressed bentonite block or basalt block cutoff collar was the most preferable scheme. Monolithic plugs of compacted earth or concrete were the next choice.

(3) Boreholes - A multiple-zoned plug of cement grout and clay-gravel slurry with bentonite pellets was the preferred plugging scheme. This same evaluation was made during the process of dominance analysis.

6.5 PRECONCEPTUAL PLUGGING SYSTEMS

In order to combine the preconceptual plugging schemes that were identified as currently feasible with the plug materials and designs recommended in the technical, dominance, and expert evaluations, the most effective preconceptual plugging systems will consist of multiple-zoned plugs with each zone designed to perform at least one of the key design functions. A brief summary of the plugging systems follows:

(1) Tunnels - Alternating zones of basalt blocks with cement-mortared joints, zones of concrete with copper flashing, and cutoff collar zones of clay-sand slurry; cement grout will be injected under pressure to treat the disturbed rock zone and the zone of contact between the concrete and the tunnel crown.

(2) Shafts - Zones of compacted sandy clay alternating with cutoff collar zones of concrete; cement grout

will be injected, under pressure, to treat the disturbed rock zone and the zone of contact between the concrete and the top of the cutoff collar recess.

(3) Boreholes - Zones of gravel-clay slurry with bentonite pellets alternating with zones of cement grout.

Preliminary calculations during the technical analysis suggest that tunnel plug lengths of 300 m would appear to be suitable to retard fluid flow.

A necessary component of any final plugging system design will be the instrumentation to monitor the quality of plug materials and placement techniques and plug performance. Quality assurance and some in-situ properties equipment and techniques are covered adequately by relevant published standards, whereas some in-situ properties and most long-term performance instrumentation are generally state-of-the-art nonstandard apparatus. Based upon the distances between sensors and readout devices, the required signal strength, and demonstrated long history of use, electric, vibrating-wire instrumentation appears to be the most feasible means currently available to monitor fluid pressures, plug and rock stresses, and plug and rock strains.

6.6 RECOMMENDATIONS

Despite the limitations and uncertainties associated with the preliminary analyses and results presented in this report, helpful insights into the relative merits and drawbacks of alternative plug schemes were obtained. In order to enhance these preliminary analyses and results, it will now be necessary to use more sophisticated modeling techniques and analyses, such as discussed in Section 3.1.2.2. Much of the data needed to implement these detailed studies can be obtained from full-scale field tests that have been carefully planned and implemented, as well as from instrumentation that is installed before, during, and after the excavation of tunnels, shafts, and repositories. The recommendations for feasible approaches to enhancing the analyses, results, and designs presented in this report are:

(1) A Shallow Borehole Plugging Test (SBPT) is proposed close to the Near-Surface Test Facility. The test is tentatively conceived as a series of boreholes about 15 m deep, 8 to 10 cm inches in diameter, drilled into basalt. Borehole configurations incorporating various plug enhancement features (e.g., underreamed cutoffs at intervals along the borehole) should be considered. Drilling practice and experience at the Hanford Site and elsewhere should be reviewed for implications to borehole plugging performance. General and special problems of plugging boreholes studied by WCC and others in previous research should be reviewed with respect to key performance criteria that can be usefully demonstrated in the shallow borehole tests. Leading candidate plugging materials and plug placement schemes that could be accommodated in this field program should be selected for this test, and guidelines for the SBPT must be prepared. Performance objectives must be designated and performance monitoring instrumentation or other confirmation testing (e.g., over coring plug intervals for laboratory testing) should be evaluated and techniques specified.

(2) Instrumentation should be installed before, during, and after the excavation of tunnels, shafts, and repositories

to monitor rock behavior. The rationale for this instrumentation is threefold: (1) provide data for detailed analyses and final plug design; (2) maintain quality control and continuous safety surveillance during excavation, radioactive waste storage, and plugging operations so that the zone of linear deformation should be kept to 1/6 of tunnel diameter; and (3) allow for continuity of information from the various contractors involved in excavation operations to the contractors involved in backfilling and plugging operations.

(3) The current analysis has concentrated on examining what might be considered design failure possibilities, such as seepage through a plug or failure under hydraulic loads. Future phases of the analyses should include a wider range of failure, such as creep failure of 'soft' plugs, piping, plug solutioning, or dispersion. Techniques that are particularly applicable in this regard involve the use of event trees and fault trees. Using these techniques, scenarios can be developed for a number of difficult failure modes, and probabilities of occurrences can be estimated for selected failure modes. Examples of these techniques are given by Lee and others (1978).

(4) In addition to instrumentation, quality assurance policies and procedures must be implemented such that individuals who will implement final plug design and placement are provided with pertinent information during the period of repository excavation and radioactive waste storage. Such continuity of information is imperative for economical and effective plug design and placement.

(5) Consideration should be given to using a tunnel boring machine to construct a circular tunnel in the area of future plugs.

(6) Future applied research and engineering study for borehole plugging should include effort in several important areas that became known during the present work. For example, properties of self-cementing natural materials (such as ground basalt) and the effects of host rock fracturing and grouting, including the use of silica grouts, should be investigated.

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APPENDIX A

PRECONCEPTUAL DESIGN CONDITIONS OF THE PLUG ENVIRONMENT

INTRODUCTION

This appendix presents a listing, provided in Table A-1, of assumed preconceptual design conditions of the plug environment for the Basalt Borehole Plugging Program. The list is divided into two basic elements: assumed physical conditions and values, and assumed chemical conditions and values. These conditions and values are tabulated with respect to four subsurface "micro-environments": boreholes starting at the surface, boreholes starting in the subsurface, tunnels, and shafts. The physical and chemical conditions included in this document are based primarily on published data, on data transmitted from personal communication by Rockwell to Woodward-Clyde Consultants and, to a lesser extent, on subjective judgment. The data base from which these conditions and values were obtained is tabulated in Table A-II, and the publications, containing the complete data sets, are listed in Appendix A references. The design conditions contained in this document are preliminary and tentative; however, they appear reasonable in the light of current knowledge or concepts and will be used until confirmatory data become available.

In general, the "assumed values," listed in Table A-I under the headings "Boreholes that Start at the Surface" and "Shafts," represent the average value obtained from one or more data sets representing a range of depths and variations in material. Where several data sets were available, a weighted average based upon the number of tests was used. The "assumed values" listed for "Boreholes that Start at the Subsurface" and for "Tunnels" were based on data from the Umtanum flow, where such data were available. Data from the Pomona flow, or from the depth range within which the repository is to be locted, were given the next order of priority in the absence of data specifically designated as being obtained form the Umtanum flow. Finally, data from Columbia Plateau basalts were given precedence over data obtained from materials from other sources. The values presented for conditions for which no laboratory or field data are available are highly subjective and should be viewed as preliminary working hypotheses.

This is intended to be a working document that may be revised; therefore, the conditions and values presented herein should not be considered as final. Most assumptions are based on a relatively limited number of laboratory tests of small samples, and they may not be entirely representative of average in-situ conditions that may be encountered during actual excavation of the repository. The greatest degree of relative reliability is probably the chemical data obtained for ground water extracted from depths at which the repository is likely to be located. The least reliable laboratory data are those obtained for sonic velocities and for permeabilities. Field data on the hydraulic gradient (to the extent that they are available) are equivocal. Thus, for a variety of reasons, it is anticipated that some of the assumed values presented herein will be modified or superceded as additional data become available. The emphasis of future data gathering efforts should be on those parameters that are found to have the greatest effect on the results of probabilistic, numerical, and/or other analyses. These may be ascertained through the application of sensitivity analysis.

TABLE A-I
PRECONCEPTUAL DESIGN CONDITIONS

PRECONCEPTUAL DESIGN CONDITIONS	BOREHOLES THAT START AT THE SURFACE	BOREHOLES THAT START IN THE SUBSURFACE	TUNNELS	SHAFTS
1.0 PHYSICAL PARAMETERS				
1.1 <u>Thermal Properties and Conditions</u>				
1.1.1 Specific Heat		<u>Assumed Value</u> 0.319 cal/gm°C at 100°C <u>Range of Values</u> (0.17 cal/gm°C at 38°C) to (0.585 cal/gm°C at 300°C) <u>Comments</u> Varies with temperature. Assumed value is average for Pomona flow.		
1.1.2 Thermal Conductivity	<u>Assumed Value</u> 1.05×10^{-2} W/cm°K <u>Range of Values</u> $(0.654 \text{ to } 1.28) \times 10^{-2}$ W/cm°K <u>Comments</u> 100°C	<u>Assumed Value</u> 1.188×10^{-2} W/cm°K at 100°C <u>Range of Values</u> $(0.799 \text{ to } 1.720) \times 10^{-2}$ W/cm°K at 100°C <u>Comments</u> 1,000 to 1,470 m		<u>Assumed Value</u> 1.05×10^{-2} W/cm°K <u>Range of Values</u> $(0.654 \text{ to } 1.28) \times 10^{-2}$ W/cm°K <u>Comments</u> 100°C
1.1.3 Thermal Diffusivity		<u>Assumed Value</u> 0.00511 cm^2/second at 93°C <u>Range of Values</u> (0.00441 to 0.0080 cm^2/second at 316°C) to (0.00532 cm^2/second at 38°C) <u>Comments</u> Varies with temperature.		

TABLE A-I (continued)

PRECONCEPTUAL DESIGN CONDITIONS	BOREHOLES THAT START AT THE SURFACE	BOREHOLES THAT START IN THE SUBSURFACE	TUNNELS	SHAFTS
1.1.4 Thermal Expansion Coefficient	Value varies with density; empirical equation of best fit line is: $\alpha = 1.11 + (2.28 \times \rho)$ where α = microstrains per degree centigrade ρ = grams per cc			
1.1.5 Temperature	<u>Assumed Values</u> 42°C <u>Range of Values</u> 15 to 70°C <u>Comments</u> Average from ground surface to Umtanum.	<u>Assumed Value</u> 60°C <u>Range of Values</u> 45 to 70°C <u>Comments</u> Umtanum Benson (1978) p. 17 *and Fig. 2; p. 3.*	<u>Assumed Value</u> 60°C <u>Range of Values</u> 45 to 70°C <u>Comments</u> Umtanum Benson (1978) p. 17 *and Fig. 2; p. 3.*	<u>Assumed Value</u> 42°C <u>Range of Values</u> 15 to 70°C <u>Comments</u> Average from ground surface to Umtanum.
1.1.6 Temperature of Plug and Wall Rock (Operating Conditions)	N. A.	<u>Assumptions</u> Temperature of plug will reach maximum of 100°C, then will cool to about 50°C.		

TABLE A-I (continued)

PRECONCEPTUAL DESIGN CONDITIONS	BOREHOLES THAT START AT THE SURFACE	BOREHOLES THAT START IN THE SUBSURFACE	TUNNELS	SHAFTS
1.2 Hydraulic Properties and Conditions				
1.2.1 Distance to Nearest Potentially Permeable Zone	Assumed Value 0 m Range of Values 0 to ? Comments Hole may penetrate zone where irrigation water may be collected and returned to the biosphere.	Assumed Value 30 m Range of Values 30 to 50 m Comments Assumes repository flow is 60 to 100 m thick.	Assumed Value 25 m Range of Values 25 to 45 m Comments Assumes repository flow is 60 to 100 m thick.	Assumed Value 0 m Range of Values 0 to ? Comments Shaft may penetrate zone where irrigation water may be collected and returned to the biosphere.
1.2.2 Distance to nearest pumped aquifer	Assumed Value 0 m Range of Values 0 to ? Comments Hole may penetrate Vantage Member.	Assumed Value 250 m Range of Values 250 to 600 m Comments Assumes Vantage Member is nearest pumped aquifer and repository flow is 250 to 600 m below this horizon.	Assumed Value 250 m Range of Values 250 to 600 m Comments Assumes Vantage Member is nearest pumped aquifer and repository flow is 250 to 600 m below this horizon.	Assumed Value 0 m Range of Values 0 to ? Comments Shaft will penetrate Vantage Member.

TABLE A-I (continued)

PRECONCEPTUAL DESIGN CONDITIONS	BOREHOLES THAT START AT THE SURFACE	BOREHOLES THAT START IN THE SUBSURFACE	TUNNELS	SHAFTS
1.2.3 Distance to Nearest Pumpable Aquifer	Assumed Value 0 m Range of Values 0 to 600 m Comments Assumes hole stops at Vantage Member and that pumpable aquifer may exist at repository flow boundary.	Assumed Value 400 m Range of Values 30 to 600 m Comments Assumes holes are at some distance below the Vantage Member and another lower aquifer.	Assumed Value 375 m Range of Values 25 to 600 m Comments Assumes holes are at some distance below the Vantage Member and another lower aquifer.	Assumed Value 0 m Range of Values 0 to ? m Comments Assumes access shafts will penetrate all potential aquifers.
1.2.4 Hydraulic Conductivity (Permeability Coefficient)	Assumed Value 10^{-9} cm/sec Range of Values 10^{-3} to 10^{-13} cm/sec Comments High values in flow tops.			
1.2.5 Transmissivity	Assumed Value 0.20 m^2/day Range of Values (1.6×10^{-3}) to 7.2 m^2/day			
1.2.6 Apparent Porosity	Assumed Value 1.24% Range of Values 1.0 to 2.4% Comments Pomona flow.			

TABLE A-I (continued)

<table>
<tr><th>PRECONCEPTUAL DESIGN CONDITIONS</th><th>BOREHOLES THAT START AT THE SURFACE</th><th>BOREHOLES THAT START IN THE SUBSURFACE</th><th>TUNNELS</th><th>SHAFTS</th></tr>
<tr><td>1.2.7 Hydraulic Gradient (Horizontal) (Pre-mining)</td><td colspan="4"><u>Assumed Value</u>
1×10^{-4}

<u>Range of Values</u>
(5×10^{-5}) to (5×10^{-4})

<u>Comments</u>
Deju and others (1978), Table I, p. 9.</td></tr>
<tr><td>1.2.8 Hydraulic Gradient (Vertical) (Pre-mining)</td><td colspan="4"><u>Assumed Value</u>
1×10^{-3}

<u>Range of Values</u>
(5×10^{-4}) to (4×10^{-1})

<u>Comments</u>
Deju and others (1978), Table I, p. 9.</td></tr>
<tr><td>1.2.9 Long-Term Hydraulic Gradients (with thermal influence)</td><td colspan="4"><u>Assumed Value</u>
1 m/km horizontal and
1 m/100 m upward

<u>Unknown</u>
Steady state flow conditions
(expanding thermal effects)</td></tr>
</table>

TABLE A-1 (continued)

PRECONCEPTUAL DESIGN CONDITIONS	BOREHOLES THAT START AT THE SURFACE	BOREHOLES THAT START IN THE SUBSURFACE	TUNNELS	SHAFTS
1.2.10 Rewatering	N. A.	N. A.	<u>Assumptions</u> *Natural rewatering takes 10 years to fill* repository. Maximum differential hydraulic head to **be studied is 1,000 m on plug pushing <u>in</u> toward** repository due to shaft or borehole filling with water while repository is dry. Maximum differential hydraulic head to be studied is 160 m on plug pushing <u>out</u> due to heating of water and steam in repository. <u>Unknowns</u> Natural or accelerated? How long will rewatering take? Will plug dry out? How long will repository be exposed to steam? What is the worst differential head on plug during rewatering? <u>Comments</u> The actual time required to rewater the excavation will be a function of both permeability of the wall rock and the void space left in the backfill.	
1.2.11 Hydrostatic Head	<u>Assumed Value, MPa</u> 10^{-2} z, where z = depth (in meters) <u>Range of Values</u> 0 to 15 MPa	<u>Assumed Value, MPa</u> 10^{-2} z, where z = depth (in meters) <u>Range of Values</u> 10 to 15 MPa	<u>Assumed Value, MPa</u> 10^{-2} z, where z = depth (in meters) <u>Range of Values</u> 10 to 15 MPa	<u>Assumed Value, MPa</u> 10^{-2}z, where z = depth (in meters) <u>Range of Values</u> 0 to 15 MPa
1.2.12 Moisture Conditions of Holes at Plug Seat	<u>Assumed Value</u> Wet <u>Range of Values</u> None <u>Comments</u> Assume that plugs will be placed in wet boreholes.		<u>Assumed Value</u> Dry <u>Range of Values</u> Dry to Wet <u>Comments</u> Maintained dry for plug placement.	

TABLE A-I (continued)

PRECONCEPTUAL DESIGN CONDITIONS	BOREHOLES THAT START AT THE SURFACE	BOREHOLES THAT START IN THE SUBSURFACE	TUNNELS	SHAFTS
1.3 Mechanical Properties and Conditions				
1.3.1 Thickness of Repository Flow	N.A.	Assumed Value 60 m Range of Values 60 to 100 m		N.A.
1.3.2 Fracture Spacing	Assumed Value 10 per meter Range of Values 1 to 28 per meter Comments Well DH-5 Long (1978)			
1.3.3 Casings/Linings of Plug Seats	Assumed Value Uncased Range of Values Casing Comments Assumes casing will be removed prior to plugging.	Assumed Value Uncased Range of Values Uncased or filled with grout or steel Comments Assumes open holes will be uncased.	Assumed Value Unlined Range of Values Unlined to lined with shotcrete, gunite, concrete, etc.	Assumed Value Lined Range of Values Unlined to lined Comments Assumes lining may be removed prior to plugging.
1.3.4 Radius of Induced Fracturing Around Hole	Assumed Value No fracturing	Assumed Value No fracturing	Data Needed	Data Needed

TABLE A-I (continued)

PRECONCEPTUAL DESIGN CONDITIONS	BOREHOLES THAT START AT THE SURFACE	BOREHOLES THAT START IN THE SUBSURFACE	TUNNELS	SHAFTS
1.3.5 Wall Rock Type at Plug Seat	Assumed Value Basalt and basalt interflow material Range of Values Basalt, flow tops, and sedimentary units Comments Hole intersects various rock types.	Assumed Value Basalt Range of Values None Comments Hole is within repository flow.	Assumed Value Basalt Range of Values None Comments Hole is within repository flow.	Assumed Value Basalt and basalt interflow material Range of Values Basalt, flow tops, and sedimentary units Comments Hole intersects various rock types.
1.3.6 Hole Diameter at Repository Depth	Assumed Value 17 cm Range of Values 5 to 25 cm Comments Holes smaller than 10 cm will probably be re-drilled to a larger diameter.	Assumed Value 10 cm Range of Values 7 to 14 cm	Assumed Value 7 m Range of Values 6 to 10 cm	Assumed Value 6 m Range of Values 2 to 9 m
1.3.7 Hole Depth-Length	Assumed Value 1,000 m Range of Values 900 to 1,500 m Comments Assumes repository depth in excess of 900 m.	Assumed Value 15 m Range of Values 5 to 50 m Comments Assumes holes will be exploratory or for advancing tunnels.	Assumed Value 3 km Range of Values 3 to 8 km Comments Assumes tunnels will be approximately 3 km long.	Assumed Value 1,000 m Range of Values 900 to 1,500 m Comments Assumes repository depth to exceed 900 m.

TABLE A-I (continued)

PRECONCEPTUAL DESIGN CONDITIONS	BOREHOLES THAT START AT THE SURFACE	BOREHOLES THAT START IN THE SUBSURFACE	TUNNELS	SHAFTS
1.3.8 Lithostatic Pressure (Horizontal) (Cook, 1977)	<u>Assumed Maximum Stress (for z > 100 m)</u> 27.3 + 0.0218 z where z = depth (in meters) <u>Range of Values</u> (23.5 + 0.0188 z) to (30.4 + 0.0243 z) <u>Assumed Minimum Stress (for z > 100 m)</u> 2.73 + 0.011 z <u>Range of Values</u> (2.35 + 0.0094 z) to (3.04 + 0.0122 z)		<u>Assumed Maximum Stress</u> 49 MPa <u>Range of Values</u> 42 to 55 MPa @ 1,000 m <u>Assumed Minimum Stress</u> 14 MPa <u>Range of Values</u> 12 to 15 MPa @ 1,000 m	<u>Comments</u> See data at left for "boreholes."
1.3.9 Lithostatic Pressure (Vertical)	<u>Assumed Value</u> 21 MPa <u>Range of Values</u> 0 to 42 MPa <u>Comments</u> Average vertical stress from surface to repository depth.	<u>Assumed Value</u> 35 MPa <u>Range of Values</u> 28 to 42 MPa <u>Comments</u> Vertical stress between 1,000 and 1,500 m	<u>Assumed Value</u> 35 MPa <u>Range of Values</u> 28 to 42 MPa <u>Comments</u> Vertical stress between 1,000 and 1,500 m. Benson (1978) calculated a pressure of 270 bars.	<u>Assumed Value</u> 21 MPa <u>Range of Values</u> 0 to 42 MPa <u>Comments</u> Average vertical stress from surface to repository depth.
1.3.10 Angle of Internal Friction	<u>Assumed Value</u> 46 degrees <u>Range of Values</u> 28 to 58 degrees <u>Comments</u> Colorado School Mines (1978)			

TABLE A-I (continued)

PRECONCEPTUAL DESIGN CONDITIONS	BOREHOLES THAT START AT THE SURFACE	BOREHOLES THAT START IN THE SUBSURFACE	TUNNELS	SHAFTS
1.3.11 Cohesion	Assumed Value 32 MPa Range of Values 15 to 38 MPa Comments Value for basalt.			
1.3.12 Density (Bulk)	Assumed Value 2.72 gm/cc Range of Values 1.75 to 2.88 gm/cc Comments DC-11; DH-2,3,4,5	Assumed Value 2.79 gm/cc Range of Values 2.67 to 2.85 gm/cc Comments DH-3,4,5; 1,009 to 1,475 m		Assumed Value 2.72 gm/cc Range of Values 1.75 to 2.88 gm/cc Comments DC-11; DH-2,3,4,5
1.3.13 Density (Grain)	Assumed Value 2.87 gm/cc Range of Values 2.4 to 3.1 gm/cc			
1.3.14 Poisson's Ratio	Assumed Value 0.249 Range of Values 0.115 to 0.513 Comments 81 Triax tests, various depths; Colorado School of Mines (1978)	Assumed Value 0.259 Range of Values 0.142 to 0.513 Comments 36 Triax tests, 1,035 to 1,470 m; Colorado School of Mines (1978)		Assumed Value 0.249 Range of Values 0.115 to 0.513 Comments 81 Triax tests, various depths; Colorado School of Mines (1978)

TABLE A-I (continued)

PRECONCEPTUAL DESIGN CONDITIONS	BOREHOLES THAT START AT THE SURFACE	BOREHOLES THAT START IN THE SUBSURFACE	TUNNELS	SHAFTS
1.3.15 Rigidity Modulus	<u>Assumed Value</u> 33.5 GPa <u>Range of Values</u> 28.4 to 41.6 GPa <u>Comments</u> Axial values from dynamic tests.			
1.3.16 Rupture Modulus	<u>Assumed Value</u> 24 MPa <u>Range of Values</u> 2.4 to 47.8 MPa <u>Comments</u> Pomona flow.			
1.3.17 Tensile Strength	<u>Assumed Value</u> 21 MPa <u>Range of Values</u> 15 to 28.5 MPa <u>Assumed Value</u> Pomona flow			
1.3.18 Triaxial Compressive Strength	<u>Comments</u> See 1.3.10 and 1.3.11 for data to plot strength envelope.			

TABLE A-I (continued)

PRECONCEPTUAL DESIGN CONDITIONS	BOREHOLES THAT START AT THE SURFACE	BOREHOLES THAT START IN THE SUBSURFACE	TUNNELS	SHAFTS
1.3.19 Uniaxial Compressive Strength	Assumed Value 218 MPa Range of Values 4 to 378 MPa Comments DC-11; DH-2,3,4,5; Colorado School of Mines (1978)	Assumed Value 219 MPa Range of Values 86 to 378 MPa Comments DH-3,4,5; 1035 to 1470 m; Colorado School of Mines (1978)		Assumed Value 218 MPa Range of Values 4 to 378 MPa Comments DC-11; DH-2,3,4,5, Colorado School of Mines (1978)
1.3.20 Young's Modulus (Dynamic)	Assumed Value 54.2 GPa Range of Values 0.38 to 165 GPa Comments Various depths	Assumed Value 51 GPa Range of Values 2.65 to 142 GPa Comments 1,000 to 1,470 m		Assumed Value 54.2 GPa Range of Values 0.38 to 165 GPa Comments Various depths
1.3.21 Young's Modulus (Static)		Assumed Value 65.4 GPa Range of Values 27.4 to 121.6 GPa Comments Triax tests, 1,035 to 1,470 m.		

TABLE A-I (continued)

PRECONCEPTUAL DESIGN CONDITIONS	BOREHOLES THAT START AT THE SURFACE	BOREHOLES THAT START IN THE SUBSURFACE	TUNNELS	SHAFTS
2.0 GEOCHEMICAL CONDITIONS				
2.1 Ground-water Chemistry				
2.1.1 Bicarbonate	Assumed Value 90 mg/l Range of Values 2 to 315 mg/l Comments Average	Assumed Value 23 mg/l Range of Values single sample Comments Umtanum	Assumed Value 23 mg/l Range of Values single sample Comments Umtanum	Assumed Value 90 mg/l Range of Values 2 to 315 mg/l Comments Average
2.1.2 Boron	Assumed Value 0.38 mg/l Range of Values 0 to 0.94 mg/l Comments Average; LaSala and Doty (1971), Table 7.	Assumed Value 0.17 mg/l Range of Values single sample Comments ARH-DC-1, 978 to 990 m; LaSala and Doty (1971), Table 7.	Assumed Value 0.17 mg/l Range of Values single sample Comments ARH-DC-1, 978 to 990 m; LaSala and Doty (1971), Table 7.	Assumed Value 0.38 mg/l Range of Values 0 to 0.94 mg/l Comments Average; LaSala and Doty (1971), Table 7.
2.1.3 Calcium	Assumed Value 10.8 mg/l Range of Values 0.5 to 72 mg/l Comments Average	Assumed Value 1.3 mg/l Range of Values single sample Comments Umtanum	Assumed Value 1.3 mg/l Range of Values single sample Comments Umtanum	Assumed Value 10.8 mg/l Range of Values 0.5 to 72 mg/l Comments Average

TABLE A-I (continued)

PRECONCEPTUAL DESIGN CONDITIONS	BOREHOLES THAT START AT THE SURFACE	BOREHOLES THAT START IN THE SUBSURFACE	TUNNELS	SHAFTS
2.1.4 Carbonate	Assumed Value 35 mg/l Range of Values 0 to 125 mg/l Comments Average	Assumed Value 17.3 mg/l Range of Values single sample Comments Umtanum	Assumed Value 17.3 mg/l Range of Values single sample Comments Umtanum	Assumed Value 35 mg/l Range of Values 0 to 125 mg/l Comments Average
2.1.5 Chloride	Assumed Value 64 mg/l Range of Values 3 to 148 mg/l Comments Average	Assumed Value 148 mg/l Range of Values single sample Comments Umtanum	Assumed Value 148 mg/l Range of Values single sample Comments Umtanum	Assumed Value 64 mg/l Range of Values 3 to 148 mg/l Comments Average
2.1.6 Fluoride	Assumed Value 29.5 mg/l Range of Values 20 to 41 mg/l Comments Average	Assumed Value 39 mg/l Range of Values 37 to 41 mg/l Comments Umtanum	Assumed Value 39 mg/l Range of Values 37 to 41 mg/l Comments Umtanum	Assumed Value 29.5 mg/l Range of Values 20 to 41 mg/l Comments Average
2.1.7 Hardness, Total	Assumed Value 56 mg/l Range of Values 1 to 220 mg/l Comments Average	Assumed Value 35 mg/l Range of Values single sample Comments Umtanum	Assumed Value 35 mg/l Range of Values single sample Comments Umtanum	Assumed Value 56 mg/l Range of Values 1 to 220 mg/l Comments Average

TABLE A-I (continued)

PRECONCEPTUAL DESIGN CONDITIONS	BOREHOLES THAT START AT THE SURFACE	BOREHOLES THAT START IN THE SUBSURFACE	TUNNELS	SHAFTS
2.1.8 Iron	Assumed Value 0.47 mg/l Range of Values 0 to 2.1 mg/l Comments ARH-DC-1, Average	Assumed Value 0.65 mg/l Range of Values single sample Comments ARH-DC-1, 978 to 990 m	Assumed Value 0.65 mg/l Range of Values single sample Comments ARH-DC-1, 978 to 990 m	Assumed Value 0.47 mg/l Range of Values 0 to 2.1 mg/l Comments ARH-DC-1, Average
2.1.9 Magnesium	Assumed Value 3 mg/l Range of Values 0 to 14 mg/l Comments Average	Assumed Value 0.1 mg/l Range of Values single sample Comments Umtanum	Assumed Value 0.1 mg/l Range of Values single sample Comments Umtanum	Assumed Value 3 mg/l Range of Values 0 to 14 mg/l Comments Average
2.1.10 Nitrate	Assumed Value 0.2 mg/l Range of Values 0 to 0.5 mg/l Comments ARH-DC-1, Average	Assumed Value 0.2 mg/l Range of Values single sample Comments ARH-DC-1, 978 to 990 m	Assumed Value 0.2 mg/l Range of Values single sample Comments ARH-DC-1, 978 to 990 m	Assumed Value 0.2 mg/l Range of Values 0 to 0.5 mg/l Comments ARH-DC-1, Average
2.1.11 pH	Assumed Value 8.8 Range of Values 7.3 to 10 Comments Average	Assumed Value 10 Range of Values single sample Comments Umtanum	Assumed Value 10 Range of Values single sample Comments Umtanum	Assumed Value 8.8 Range of Values 7.3 to 10 Comments Average

TABLE A-I (continued)

PRECONCEPTUAL DESIGN CONDITIONS	BOREHOLES THAT START AT THE SURFACE	BOREHOLES THAT START IN THE SUBSURFACE	TUNNELS	SHAFTS
2.1.12 Phosphate	Assumed Value 0.08 mg/l Range of Values 0.01 to 0.25 mg/l Comments ARH-DC-1, Average	Assumed Value 0.02 mg/l Range of Values single sample Comments ARH-DC-1, 978 to 990 m	Assumed Value 0.02 mg/l Range of Values single sample Comments ARH-DC-1, 978 to 990 m	Assumed Value 0.08 mg/l Range of Values 0.01 to 0.25 mg/l Comments ARH-DC-1, Average
2.1.13 Potassium	Assumed Value 11 mg/l Range of Values 3 to 15 mg/l Comments 110 to 684 m	Assumed Value 5.9 mg/l Range of Values single sample Comments 978 to 990 m	Assumed Value 5.9 mg/l Range of Values single sample Comments 978 to 990 m	Assumed Value 11 mg/l Range of Values 3 to 15 mg/l Comments 110 to 684 m
2.1.14 Silica	Assumed Value 53 mg/l Range of Values 22.5 to 105 mg/l Comments Average	Assumed Value 53.8 mg/l Range of Values single sample Comments Umtanum	Assumed Value 53.8 mg/l Range of Values single sample Comments Umtanum	Assumed Value 53 mg/l Range of Values 22.5 to 105 mg/l Comments Average
2.1.15 Sodium	Assumed Value 99 mg/l Range of Values 29 to 242 mg/l Comments Average	Assumed Value 242 mg/l Range of Values single sample Comments Umtanum	Assumed Value 242 mg/l Range of Values single sample Comments Umtanum	Assumed Value 99 mg/l Range of Values 29 to 242 mg/l Comments Average

TABLE A-I (continued)

PRECONCEPTUAL DESIGN CONDITIONS	BOREHOLES THAT START AT THE SURFACE	BOREHOLES THAT START IN THE SUBSURFACE	TUNNELS	SHAFTS
2.1.16 Sulfate	Assumed Value 30 mg/l Range of Values 0 to 150 mg/l Comments Average	Assumed Value 96 mg/l Range of Values single sample Comments Umtanum	Assumed Value 96 mg/l Range of Values single sample Comments Umtanum	Assumed Value 30 mg/l Range of Values 0 to 150 mg/l Comments Average
2.1.17 Eh	Assumed to be reducing at plug seats below the water table. The presence of iron pyrite as a stable secondary mineral phase suggests an Eh range of -0.2 to -0.3 volts (Garrels and Christ, 1965, p. 224). Other secondary minerals present at projected repository depths are also stable in this Eh range and at the assumed pH of approximately 10 (see 2.1.11, above). Both tunnels and shafts will have an oxidizing environment during repository operations prior to plug and backfill placement.			
2.2 Secondary Minerals	Reported Minerals Clinoptilolite Nontronite Cristobalite Quartz Calcite Gypsum Potassium Feldspar Mordenite Pyrite Apatite Opal Comments Benson (1978), page 16			

TABLE A-II
PHYSICAL DATA COMPILATION

PARAMETER	AVERAGE VALUE	RANGE OF VALUES	UNITS	NO. OF TESTS	REMARKS	DATA SOURCE AUTHOR (YEAR)	TABLE	PAGE
THERMAL PROPERTIES								
Specific Heat								
	0.319	0.288 to 0.355	cal/gm °C	3	Cp 100°C Pomona flow	Duvall and others (1978)	XII	
	0.425	0.394 to 0.460	cal/gm °C	3	Cp 200°C Pomona flow	Duvall and others (1978)	XII	
	0.538	0.474 to 0.585	cal/gm °C	3	Cp 300°C Pomona flow	Duvall and others (1978)	XII	
	0.35	0.23 to 0.25	cal/gm °C	?	"Average" is Columbia Basalt; range is for "average" basalt.	Board (1978)	II	
	0.175	0.174 to 0.176	cal/gm °C	2	37.8°C	ARHCO (1976)	I	120
	0.186	0.186 to 0.187	cal/gm °C	2	93.3°C	ARHCO (1976)	I	120
	0.197	0.197 to 0.198	cal/gm °C	2	149°C	ARHCO (1976)	I	120
	0.208	0.207 to 0.210	cal/gm °C	2	204°C	ARHCO (1976)	I	120
	0.219	0.217 to 0.222	cal/gm °C	2	260°C	ARHCO (1976)	I	120
	0.230	0.227 to 0.234	cal/gm °C	2	316°C	ARHCO (1976)	I	120
	1.0	0.95 to 1.05	kj/kg °K			Agapito and others (1977)	I	
Thermal Conductivity	0.349	0.310 to 0.384	cal/sec m°C	3	K150°C	Duvall and others (1978)	XI	
	0.347	0.308 to 0.383	cal/sec m°C	3	K200°C	Duvall and others (1978)	XI	
	0.348	0.303 to 0.383	cal/sec m°C	3	K250°C	Duvall and others (1978)	XI	
	0.36	0.335 to 1.0	cal/sec m°C	?	Cites Duvall and others (1978)	Board (1978)	II	
	0.258	0.243 to 0.272	cal/sec m°C	2	37.8°C	ARHCO (1976)	I	120
	0.267	0.249 to 0.284	cal/sec m°C	2	93.3°C	ARHCO (1976)	I	120
	0.275	0.255 to 0.295	cal/sec m°C	2	149°C	ARHCO (1976)	I	120
	0.283	0.260 to 0.305	cal/sec m°C	2	204°C	ARHCO (1976)	I	120
	0.290	0.264 to 0.315	cal/sec m°C	2	260°C	ARHCO (1976)	I	120
	0.300	0.267 to 0.324	cal/sec m°C	2	316°C	ARHCO (1976)	I	120
	1.5	1.4 to 2.8	w/m °K	?	373°K	Agapito and others (1977)	I	
	1.53		w/m °K	?		Agapito and others (1977)	IV	
	1.05×10^{-2}	$(0.654 \text{ to } 1.28) \times 10^{-2}$	w/cm °K	29	All samples, 100°C	Colorado Sch. Mines (1978)	Fig. 15	70
	1.48×10^{-2}	$(0.744 \text{ to } 2.256) \times 10^{-2}$	w/cm °K	29	All samples, 200°C	Colorado Sch. Mines (1978)	Fig. 15	70
	1.9×10^{-2}	$(0.783 \text{ to } 2.992) \times 10^{-2}$	w/cm °K	29	All samples, 300°C	Colorado Sch Mines (1978)	Fig. 15	70
	1.188×10^{-2}	$(0.799 \text{ to } 1.720) \times 10^{-2}$	w/cm °K	13	1,005 to 1,470 m, 100°C	Colorado Sch. Mines (1978)		71-74
	1.574×10^{-2}	$(1.047 \text{ to } 1.787) \times 10^{-2}$	w/cm °K	13	1,005 to 1,470 m, 200°C	Colorado Sch. Mines (1978)		71-74
	2.01×10^{-2}	$(1.252 \text{ to } 2.992) \times 10^{-2}$	w/cm °K	13	1,005 to 1,470 m, 300°C	Colorado Sch. Mines (1978)		71-74
Thermal Diffusivity	0.00524	0.00516 to 0.00532	cm^2/sec	2	37.8°C	ARHCO (1976)	I	120
	0.00511	0.00503 to 0.00519	cm^2/sec	2	93.3°C	ARHCO (1976)	I	120
	0.00497	0.00488 to 0.00506	cm^2/sec	2	149°C	ARHCO (1976)	I	120
	0.00482	0.00472 to 0.00493	cm^2/sec	2	204°C	ARHCO (1976)	I	120
	0.00459	0.00457 to 0.00480	cm^2/sec	2	260°C	ARHCO (1976)	I	120
	0.00454	0.00441 to 0 00467	cm^2/sec	2	316°C	ARHCO (1976)	I	120
	0.00650	0.0052 to 0.0080	cm^2/sec	2		Agapito and others (1977)	I	
Thermal Expansion Coefficient	6.5×10^{-6}	$(6.5 \text{ to } 6.7) \times 10^{-6}$	/°C	3	Pomona flow, Gable Mtn.	Duvall and others (1978)	X	
	6.6×10^{-6}	$(2.9 \text{ to } 11.6) \times 10^{-6}$	/°C	?	Columbia Plateau vs. "average"	Board (1978)	II	
	5.4×10^{-6}	$(2.9 \text{ to } 11.6) \times 10^{-6}$	/°K	?		Agapito and others (1977)	I	
	5.4×10^{-6}	$(4.3 \text{ to } 6.5) \times 10^{-6}$	/°K	?	300°K	Agapito and others (1977)	V	
					Empirical equation of best fit line $\alpha = 1.11 + (2.28 \times \rho)$ where α = micro-strains per degree centigrade; ρ = grams per cc.	Colorado Sch. Mines (1978)		66

TABLE A-II (continued)

PARAMETER	AVERAGE VALUE	RANGE OF VALUES	UNITS	NO. OF TESTS	REMARKS	DATA SOURCE AUTHOR (YEAR)	TABLE	PAGE
HYDRAULIC PROPERTIES								
Apparent Porosity	1.89%	1.60 to 2.39%	percent	3	Small samples - Pomona flow	Duvall and others (1978)	IX	
	1.24%	1.00 to 1.59%	percent	3	Large samples - Pomona flow	Duvall and others (1978)	IX	
Hydraulic Conductivity	10^{-10}	10^{-7} to 10^{-13}	cm/sec	?	Preliminary data	Biggerstaff (1978)		109
	10^{-10}	10^{-3} to 10^{-13}	m/sec	14	Vesicular and rubbly flow tops	Gephart and others (1978)	1	
	10^{-6}	10^{-6} to 10^{-7}	cm/sec	3	Papadopulos method	Science App. (1978)	2	11
	10^{-8}	10^{-6} to 10^{-8}	cm/sec	3	USBR method	Science App. (1978)	2	11
	10^{-10}	10^{-9} to 10^{-12}	cm/sec	6	Hvorslev method	Science App. (1978)	2	11
Transmissivity	21.6	0.17 to 77.9	ft^2/day	18		LaSala and Doty (1971)	4	24
MECHANICAL PROPERTIES								
Angle of Internal Friction	55°	45° to 60°	degrees	?	Summarized from Agapito and others (1977)?	Board (1978)	II	
	55°	45° to 60°	degrees			Agapito and others (1977)	I	
	52°	42° to 59°	degrees	6		Agapito and others (1977)	XIII	
Bulk Modulus	$\left(\frac{42.0}{35.5}\right) \times 10^3$	$\left(\frac{26.1}{44.8} \text{ to } \frac{54.7}{41.2}\right) \times 10^3$	MPa	19	Axial/Diametral Pomona flow	Duvall and others (1978)	VII	
Cohesion	32	15 to 38	MPa	6		Agapito and others (1977)	XIII	
Density (Bulk)	2.83	2.78 to 2.87		9	Pomona flow Gable Mtn.	Duvall and others (1978)	I	
	2.81	2.78 to 2.84		3	Pomona flow, Gable Mtn.	Duvall and others (1978)	VIII	
	2.80	2.66 to 2.94		2	37.8°C; depth 306 to 330 m	ARHCO (1976)	I	120
	2.80	2.66 to 2.94		2	93.3°C	ARHCO (1976)	I	120
	2.81	2.65 to 2.95		2	149°C	ARHCO (1976)	I	120
	2.81	2.67 to 2.95		2	204°C	ARHCO (1976)	I	120
	2.81	2.67 to 2.95		2	260°C	ARHCO (1976)	I	120
	2.81	2.67 to 2.95		2	316°C	ARHCO (1976)	I	120
	2.9	2.40 to 3.10		?		Agapito and others (1977)	I	
	2.70	2.46 to 2.90		14		Agapito and others (1977)	XI	
	2.79	2.67 to 2.85	gm/cc	26	DH-3,4,5; 1,005 to 1,470 m	Colorado Sch. Mines (1978)		7-9
	2.72	1.75 to 2.88	gm/cc	84	DC-11; DH-2,3,4,5; all samples	Colorado Sch. Mines (1978)		7-9
Density (Grain)	2.87	2.85 to 2.89		3	Pomona flow, Gable Mtn.	Duvall and others (1978)	VIII	
	2.87	2.4 to 3.1		?	Cites Duval and others (1978)	Board (1978)	II	

TABLE A-II (continued)

PARAMETER	AVERAGE VALUE	RANGE OF VALUES	UNITS	NO. OF TESTS	REMARKS	DATA SOURCE AUTHOR (YEAR)	TABLE	PAGE
Dynamic Wave Velocities	$\frac{5599}{5717}$	$\frac{5242}{5277}$ to $\frac{5991}{5937}$	ft/sec	18	Axial/diametral vs. Pomona flow, Gable Mtn.	Duvall and others (1976)	VI	
	$\frac{3480}{3832}$	$\frac{3193}{3958}$ to $\frac{3819}{3653}$	ft/sec	18	Axial/diametral vs. Pomona flow, Gable Mtn.	Duvall and others (1976)	VI	
Lame's Constant	$\frac{19.7}{9.0}$	$\frac{-1.6}{24.4}$ to $\frac{32.4}{11.1}$	MPa	19	Axial/diametral Pomona flow	Duvall and others (1978)	VII	
Poisson's Ratio (Dynamic)	$\frac{0.183}{0.069}$	$\frac{-0.021}{0.195}$ to $\frac{0.229}{0.10}$		19	Axial/diametral Pomona flow	Duvall and others (1978)	VII	
Poisson's Ratio (Static)	0.25	0.191 to 0.290		9	Uniaxial tests; Pomona flow	Duvall and others (1978)	V	
	0.25	0.215 to 0.286		9	Triaxial tests; Pomona flow	Duvall and others (1978)	V	
	0.26	0.22 to 0.28		?		Agapito and others (1977)	I	
	0.17	0.05 to 0.31		12	Bacon Siphon, Columbia Basin	Agapito and others (1977)	XI	
	0.249	0.115 to 0.513		81	Triax - all samples	Colorado Sch. Mines		37-39
	0.259	0.130 to 0.554		84	Uniax - all samples	Colorado Sch. Mines		40-42
	0.259	0.142 to 0.513		36	Triax - 1,034 to 1,470 m	Colorado Sch. Mines		37-39
	0.254	0.130 to 0.554		41	Uniax - 1,034 to 1,470 m	Colorado Sch. Mines		40-42
Rigidity Modulus (Dynamic)	$\left(\frac{33.5}{40.5}\right) \times 10^3$	$\left(\frac{28.4}{43.6} \text{ to } \frac{41.6}{28.1}\right) \times 10^3$	MPa	19	Axial/diametral Pomona flow	Duvall and others (1978)	VII	
Rupture Modulus	24	2.42 to 47.8	MPa	12	Pomona flow, Gable Mtn.	Duvall and others (1978)	IV	
Tensile Strength	21	15 to 28.5	MPa	9	Pomona flow, Gable Mtn.	Duvall and others (1978)	II	
	21	0 to 23	MPa	?		Board (1978)	II	
	14	0 to 23	MPa	?		Agapito and others (1977)	I	
	18.4	2.8 to 33.9	MPa	6		LaSala and Doty (1971)	VI	48
Triaxial Compressive Strength	273	141 to 379	MPa	9	Pomona flow, Gable Mtn.	Duvall and others (1978)	III	
	290	16 to 638	MPa	59	Various confining pressures	Agapito and others (1977)	XII	
Uniaxial Compressive Strength	309	248 to 378	MPa	9	Pomona flow, Gable Mtn.	Duvall and others (1978)	I	
	284	0 to 400	MPa	?		Board (1978)	II	
	200	0 to 400	MPa	?		Agapito and others (1977)	I	
	159	74 to 322	MPa	6		LaSala and Doty (1971)	6	48
	195.3	84.3 to 287.9	MPa	9	DH-4, 1,177 to 1,364 m	Colorado Sch. Mines (1978)		7
	247.3	85.6 to 378.2	MPa	9	DH-5, 1,006 to 1,470 m	Colorado Sch. Mines (1978)		8
	210.4	160.6 to 304.9	MPa	5	DH-3, 1,034 to 1,069 m	Colorado Sch. Mines (1978)		9
	218	4 to 378	MPa	84	DC-11, DH-2,3,4,5, all samples	Colorado Sch. Mines (1978)		7-9

TABLE A-II (continued)

PARAMETER	AVERAGE VALUE	RANGE OF VALUES	UNITS	NO. OF TESTS	REMARKS	DATA SOURCE AUTHOR (YEAR)	TABLE	PAGE
Young's Modulus (static)	76	64 to 87	GPa	9	Uniaxial tests Pomona flow	Duvall and others (1978)	V	
	77	63.1 to 85.5	GPa	9	Triaxial tests, Pomona flow	Duvall and others (1978)	V	
	77	61 to 112	GPa	?		Board (1978)	II	
	111.5	111.5	GPa	1	Basalt. Ostritz, Germany	Agapito and others (1977)	VI	
	61	61	GPa	1	Basalt. Michigan	Agapito and others (1977)	VI	
	85	85	GPa	1	Basalt. Michigan	Agapito and others (1977)	VI	
	88.5	88.5	GPa	1	Basalt. Wisconsin	Agapito and others (1977)	VI	
	60	45 to 80	GPa	12	Bacon Siphon-Columbia Basin	Agapito and others (1977)	XI	
	6.54×10^4	$(2.74 \text{ to } 12.16) \times 10^4$	MPa	36	Triax, 1,034 to 1,470 m	Colorado Sch. Mines (1978)		37-39
	5.78×10^4	$(1.39 \text{ to } 9.45) \times 10^4$	MPa	42	Uniax, 1,006 to 1,470 m	Colorado Sch. Mines (1978)		40-42
	6.52×10^4	$(1.32 \text{ to } 12.16) \times 10^4$	MPa	81	Triax, all samples	Colorado Sch. Mines (1978)		37-39
	6.01×10^4	$(0.77 \text{ to } 9.45) \times 10^4$	MPa	84	Uniax, all samples	Colorado Sch. Mines (1978)		40-42
Young's Modulus (Dynamic)	$\left(\frac{72.7}{75.3}\right)$	$\left(\frac{69.8}{74.7} \text{ to } \frac{89.8}{98.8}\right)$	GPa	19	Uniaxial tests, Pomona flow	Duvall and others (1978)	VII	
	5.42×10^4	$(0.038 \text{ to } 16.5) \times 10^4$	MPa	214	Lab, all samples	Colorado Sch. Mines (1978)		55-60
	5.10×10^4	$(0.265 \text{ to } 14.2) \times 10^4$	MPa	110	Lab, 1,006 to 1,470 m	Colorado Sch. Mines (1978)		55-60

TABLE A-II (continued)

PARAMETERS	AVERAGE VALUE*	RANGE OF VALUES*	REMARKS	DATA SOURCE AUTHOR (YEAR)	DATA SOURCE TABLE	/ PAGE
Bicarbonate	172	115 to 315	Unconfined aquifer	ARHCO (1976)		
	152	93 to 180	Uppermost confined aquifer	ARHCO (1976)		
	56	2 to 164	Lower confined aquifers	ARHCO (1976)		
	42.8		Grande Ronde Basalt (RSH-1)	Deju (1978)	III	
	180		Mabton Member	Deju (1978)	Fig. 5	18
	23		Umtanum basalt			
	2		ARH-DC-1, 978 to 990 m	LaSala and Doty (1971)	7	50
Boron	0 17		ARH-DC-1; 978 to 990 m	LaSala and Doty (1971)	7	50
Calcium	48	31 to 72	Unconfined aquifer	ARHCO (1976)		
	15	1 to 18	Uppermost confined aquifer	ARHCO (1976)		
	0.5	0.2 to 0.8	Lower confined aquifer	ARHCO (1976)		
	6.5		Grande Ronde Basalt (RSH-1)	Deju (1978)	III	
	3.4					
	1.3		Mabton Member	Deju (1978)	Fig. 5	18
			Umtanum basalt			
	0.6		Umtanum Basalt (DC-6)	LaSala and Doty (1971)	7	50

*All values, except pH, are in mg/l

TABLE A-II (continued)

PARAMETERS	AVERAGE VALUE*	RANGE OF VALUES*	REMARKS	DATA SOURCE AUTHOR (YEAR)	DATA SOURCE TABLE	/ PAGE
Fluoride	39	37 to 41	Umtanum basalt (DC-6)			
	20		ARH-DC-1; 978 to 990 m	LaSala and Doty (1971)	7	50
Hardness, total	170	110 to 220	Unconfined aquifer	ARHCO (1976)		
	66	3 to 96	Uppermost confined aquifer	ARHCO (1976)		
	2	1 to 2	Lower confined aquifers	ARHCO (1976)		
	35		Umtanum basalt (DC-6)			
	7		ARH-DC-1; 978 to 990 m	LaSala and Doty (1971)	7	50
Iron	0.65		ARH-DC-1; 978 to 990 m	LaSala and Doty (1971)	7	50
Magnesium	12	7.1 to 14	Unconfined aquifer	ARHCO (1976)		
	7	0 to 11	Uppermost confined aquifer	ARHCO (1976)		
	0.1	0 to 0.1	Lower confined aquifer	ARHCO (1976)		
	1.0		Grande Ronde Basalt (RSH-1)	Deju (1978)	III	
	0.5		Umtanum Basalt (DC-6)	Deju (1978)	Fig. 5	18
	0.1		Mabton Member			
	0.1		ARH-DC-1; 978 to 990 m	LaSala and Doty (1971)		

*All values, except pH, are in mg/l

TABLE A-II (continued)

PARAMETERS	AVERAGE VALUE*	RANGE OF VALUES*	REMARKS	DATA SOURCE AUTHOR (YEAR)	DATA SOURCE TABLE	PAGE
Nitrate	0.2		ARH-DC-1; 978 to 990 m	LaSala and Doty (1971)	7	50
pH*	8.0	7.5 to 8.1	Unconfined aquifer	ARHCO (1976)	7	50
	8.0	7.2 to 8.7	Upper confined aquifer	ARHCO (1976)		
	9.6	8.9 to 9.9	Lower confined aquifer	ARHCO (1976)		
	7.3		Grande Ronde Basalt (RSH-1)	Deju (1978)	III	
	8.6		Mabton Member	Deju (1978)	Fig. 5	18
	10	9.9 to 10.1	Umtanum basalt (DC-6)			
	9.9		ARH-DC-1; 978 to 990 m	LaSala and Doty (1971)	7	50
Phosphate	0.2		ARH-DC-1; 978 to 990 m	LaSala and Doty (1971)	7	50
Potassium	6.8	4.6 to 13	Unconfined aquifer	ARHCO (1976)		
	9.0	4.5 to 17	Uppermost confined aquifer	ARHCO (1976)		
	4.0	3.0 to 5.9	Lower confined aquifer	ARHCO (1976)		
	9		Grande Ronde Basalt (RSH-1)	Deju (1978)	III	
	13		Mabton Member	Deju (1978)	Fig. 5	18
	3.2		Umtanum basalt (DC-6)			
	5.9		ARH-DC-1; 978 to 990 m	LaSala and Doty (1971)	7	50

*All values, except pH, are in mg/l

TABLE A-II (continued)

PARAMETERS	AVERAGE VALUE*	RANGE OF VALUES*	REMARKS	DATA SOURCE AUTHOR (YEAR)	DATA SOURCE TABLE	/ PAGE
Carbonate	0		Unconfined aquifer	ARHCO (1976)		
	3	0 to 15	Uppermost confined aquifer	ARHCO (1976)		
	87	16 to 125	Lower confined aquifer	ARHCO (1976)		
	0		Grande Ronde Basalt (RSH-1)	Deju (1978)	III	
	19		Mabton Member	Deju (1978)	Fig. 5	18
	17.3		Umtanum basalt (DC-6)			
	120		ARH-DC-1; 978 to 900 m	LaSala and Doty (1971)	7	50
Chloride	13	3.1 to 24	Unconfined aquifer	ARHCO (1976)		
	16	3.8 to 81	Uppermost confined aquifer	ARHCO (1976)		
	90	68 to 98	Lower confined aquifer	ARHCO (1976)		
	16.2		Grande Ronde Basalt (RSH-1)	Deju (1978)	III	
	66.6		Mabton Member	Deju (1978)	Fig. 5	18
	148		Umtanum basalt			
	98		ARH-DC-1; 978 to 990 m	LaSala and Doty (1971)	7	50

*All values, except pH, are in mg/l

TABLE A-II (continued)

PARAMETERS	AVERAGE VALUE*	RANGE OF VALUES*	REMARKS	DATA SOURCE AUTHOR (YEAR)	DATA SOURCE TABLE	/ PAGE
Silica (As Si)	22.5		Grande Ronde Basalt (RSH-1)	Deju (1978)	III	
	31.9		Mabton Member	Deju (1978)	Fig. 5	18
	53.8		Umtanum basalt (DC-6)			
	105		ARH-DC-1; 978 to 990 m	LaSala and Doty (1971)	7	50
Sodium	29	16 to 64	Unconfined aquifer	ARHCO (1976		
	40	4.1 to 122	Uppermost confined aquifer	ARHCO (1976)		
	168	134 to 182	Lower confined aquifers	ARHCO (1976)		
	30		Grande Ronde Basalt (RSH-1)	Deju (1978)	III	
	110		Mabton Member	Deju (1978)	Fig. 5	18
	242		Umtanum basalt (DC-6)			
	176		ARH-DC-1; 978 to 990 m	LaSala and Doty (1971)	7	50
Sulfate	58	20 to 150	Unconfined aquifer	ARHCO (1976)		
	9	0 to 29	Uppermost confined aquifer	ARCHO (1976)		
	14	10 to 21	Lower confined aquifers	ARHCO (1976)		
	23		Grande Ronde Basalt (RSH-1)	Deju (1978)	III	
	0.6		Mabton Member	Deju (1978)	Fig. 5	18
	96		Umtanum basalt			
	10		ARH-DC-1; 978 to 990 m	LaSala and Doty (1971)	7	50

*All values, except pH, are in mg/l

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APPENDIX B

THERMAL STRESS IN AN ELASTIC PLUG

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THERMAL STRESS IN AN ELASTIC PLUG

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APPENDIX B

THERMAL STRESS IN AN ELASTIC PLUG

B.1 INTRODUCTION

In all the calculations reported, the temperature is taken as uniform throughout the plug and the surrounding rock and is independent of the axial coordinate. Thermoelastic solutions were developed by Timoshenko and Goodier (1951) for the long, circular cylinder. The method herein is to apply those equations to the plug system (long circular solid cylinder) and to the surrounding rock (long, thick-wall, hollow cylinder); strain compatibility at the interface plug wall rock provides the necessary equation for resolving the problem.

B.2 THERMAL STRESS EQUATION FOR A LONG CONFINED PLUG

The thermomechanical stress-strain relations in polar coordinate for perfectly elastic long circular cylinder confined and its ends (no axial displacement) are given by

$$\mu = \frac{1+\nu}{1-\nu} \cdot \alpha \cdot \frac{1}{r} \int_{r_o}^{r} Trdr + C_1 r + \frac{C_2}{r} \quad \text{(B-1)}$$

$$\sigma_r = -\frac{\alpha E}{1-\nu} \cdot \frac{1}{r^2} \int_{r_o}^{r} Trdr + \frac{E}{1+\nu} \left\{ \frac{C_1}{1-2\nu} - \frac{C_2}{r^2} \right\} \quad \text{(B-2)}$$

$$\sigma_\theta = \frac{\alpha E}{1-\nu} \cdot \frac{1}{r^2} \int_{r_o}^{r} Trdr - \frac{\alpha ET}{1-\nu} + \frac{E}{1+\nu} \left\{ \frac{C_1}{1-2\nu} + \frac{C_2}{r^2} \right\} \quad \text{(B-3)}$$

$$\sigma_z = -\frac{\alpha E T}{1-\nu} + \frac{2\nu E C_1}{(1+\nu)\ (1-2\nu)} \tag{B-4}$$

$$\tau_{r\theta} = \tau_{rz} = \tau_{\theta z} = 0 \tag{B-5}$$

where
- E = Young's Modulus (MPa)
- ν = Poisson's Ratio (dimensionless)
- α = coefficient of thermal expansion (per °C)
- σ_r = radial stress (MPa)
- σ_θ = tangential stress (MPa)
- σ_z = axial stress (MPa)
- μ = radial displacement (meters)
- T = temperature (°C)
- r_o = internal radius of the cylinder (meters)
- r = radial distance from the center of the cylinder (meters)
- τ = shear stress (MPa).

C_1 and C_2 are two constants depending on the boundary conditions.

For a uniform temperature through the plug and its environment, integration of Equations B-1, B-2, B-3, and B-4 give:

$$\mu = \frac{(1+\nu)\alpha T}{2\ (1-\nu)} \frac{r^2-r_o{}^2}{r} + C_1 r + \frac{C2}{r} \qquad \text{(B-1')}$$

$$\sigma_r = \frac{-\ \alpha ET}{2(1-\nu)} \frac{r^2-r_o{}^2}{r^2} + \frac{E}{1+\nu}\left(\frac{C_1}{1-2\nu} - \frac{C_2}{r^2}\right) \qquad \text{(B-2')}$$

$$\sigma_\theta = \frac{\alpha ET}{2(1-\nu)} \frac{r^2-r_o{}^2}{r^2} - \frac{\alpha ET}{1-\nu} + \frac{E}{1+\nu}\left(\frac{C_1}{1-2\nu} + \frac{C_2}{r^2}\right) \qquad \text{(B-3')}$$

$$\sigma_z = \frac{-\alpha ET}{1-\nu} + \frac{2\nu EC_1}{(1+\nu)(1-2\nu)}. \qquad \text{(B-4')}$$

B.2.1 Solid Cylinder (Elastic Plug)

In this case, $r_o = 0$ in Equations B-1', B-2', B-3', and B-4'. The displacement μ must vanish for $r = 0$. Then Equation B-1' gives $C_2 = 0$. The constant C_1 is found from the condition that the external surface of the solid cylinder is submitted to a uniform stress P due to the reciprocal action of the plug and the wall rock.

$$C_1 = \frac{P\ (1+\nu)\ (1-2\nu)}{E} + \frac{\alpha\ T\ (1+\nu)\ (1-2\nu)}{2(1-\nu)}. \quad \text{(B-6)}$$

Introducing C_1 and C_2 in Equations B-1', B-2', B-3', and B-4' leads to:

$$\mu = \alpha Tr\ (1+\nu) + \frac{Pr}{E}\ (1+\nu)\ (1-2\nu) \quad \text{(B-7)}$$

$$\sigma_r = P \quad \text{(B-8)}$$

$$\sigma_\theta = P \quad \text{(B-9)}$$

$$\sigma_z = 2\nu P - E\alpha T. \quad \text{(B-10)}$$

Equations B-8, B-9, and B-10 indicate a uniform triaxial stress field throughout the elastic plug and may be simulated by triaxial test in laboratory.

B.2.2 Thick-Wall, Hollow Cylinder (Surrounding Rock)

In this case, r_o = a is the radius of the cylinder opening. The constants C_1 and C_2 are found from the condition that the internal interface of the hollow cylinder is submitted to the uniform radial stress P and that at the limit the radial displacement is zero:

$$C_1 = -\frac{\alpha T(1+\nu)}{2(1-\nu)} \qquad \text{(B-11)}$$

Using B-2, for r = a:

$$C_2 = -\frac{a^2\ \alpha T(1+\nu)}{2(1-\nu)(1-2\nu)} - \frac{Pa^2(1+\nu)}{E}. \qquad \text{(B-12)}$$

Introducing C_1 and C_2 in Equations B-1', B-2', B-3', and B-4' leads to

$$\mu = \frac{-a^2}{r}(1+\nu)\frac{P}{E} - \alpha T\frac{a^2}{r}\frac{(1+\nu)}{(1-2\nu)} \qquad \text{(B-13)}$$

$$\sigma_r = -\frac{\alpha ET}{1-2\nu} + \frac{Pa^2}{r^2} + \frac{a^2}{r^2}\left(\frac{\alpha ET}{1-2\nu}\right) \qquad \text{(B-14)}$$

$$\sigma_\theta = -\frac{\alpha ET}{1-2\nu} - \frac{Pa^2}{r^2} - \frac{a^2}{r^2}\left(\frac{\alpha ET}{1-2\nu}\right) \qquad \text{(B-15)}$$

$$\sigma_z = \frac{-\alpha ET}{(1-2\nu)}. \qquad \text{(B-16)}$$

At the internal thick wall cylinder boundary (r = a), Equations B-13, B-14, and B-15 lead to

$$\mu^a = -\frac{1+\nu}{E} Pa - \alpha Ta \frac{1+\nu}{1-2\nu} \tag{B-17}$$

$$\sigma_r^a = P \tag{B-18}$$

$$\sigma_\theta^a = -\frac{2\alpha ET}{1-2\nu} - P, \tag{B-19}$$

B.2.3 Equation of Compatibility

To insure continuity between the plug and the surrounding rock, the radial displacement of the solid cylinder shall be equal to the radial deformation of the thick wall cylinder. Thermal and elastic constants are subscripted by p for the solid cylinder and by R for the thick-wall hollow cylinder; thus, Equations B-7 and B-17 lead to

$$\alpha_p Ta\,(1+\nu_p) + \frac{Pa}{E_p}\,(1+\nu_p)(1-2\nu_p) = -\left(\frac{1+\nu_R}{E_R}\right)Pa - \alpha_R Ta\left(\frac{1+\nu_R}{1-2\nu_R}\right) \tag{B-20}$$

or

$$P = \frac{-TE_p E_R \left[\alpha_R (1+\nu_R) + \alpha_p (1+\nu_p) (1-2\nu_R)\right]}{(1-2\nu_R) \left[E_R (1+\nu_p) (1-2\nu_p) + E_p (1+\nu_R)\right]} . \qquad \text{(B-21)}$$

B.3 THERMAL STRESS IN A FREE-END ELASTIC PLUG

B.3.1 Equation of Compatibility

The thermoelastic solution in the case of a free-end plug is obtained by superimposing a uniform axial stress $\sigma_z = C_3$ to Equation B-4, which was chosen so that the resultant force on the end of the plug is zero. σ_z, in the case of a confined cylinder, is given by Equation B-10. Therefore C_3 is

$$C_3 = -2\nu_p P + E_p \alpha_p T . \qquad \text{(B-22)}$$

The stresses σ_z and σ_θ remain the same as in the confined solid cylinder and are still given by

$$\sigma_r = \sigma_\theta = P,$$

The displacement μ is, however, affected by the axial stress C_3. A term $-\nu C_3 r/E$ must be added on the right of Equation B-7 leading to

$$\mu = \alpha_p Tr + \frac{Pr}{E} (1-\nu_p) . \qquad \text{(B-23)}$$

The equation of compatibility between the plug and the surrounding rock is now given by equating 17 and B-23:

$$\alpha_p Ta + \frac{Pa}{E_p}(1-\nu_p) = \frac{-\alpha_R Ta(1+\nu_R)}{(1-2\nu_R)} - \frac{Pa(1+\nu_R)}{E_R} \qquad \text{(B-24)}$$

or

$$P = \frac{-TE_pE_R[\alpha_R(1+\nu_R) + \alpha_p(1-2\nu_R)]}{(1-2\nu_R)\,[E_R(1-\nu_p) + E_p(1+\nu_R)]} \qquad \text{(B-25)}$$

B.4 SHEAR STRESS AT THE PLUG/WALL-ROCK INTERFACE

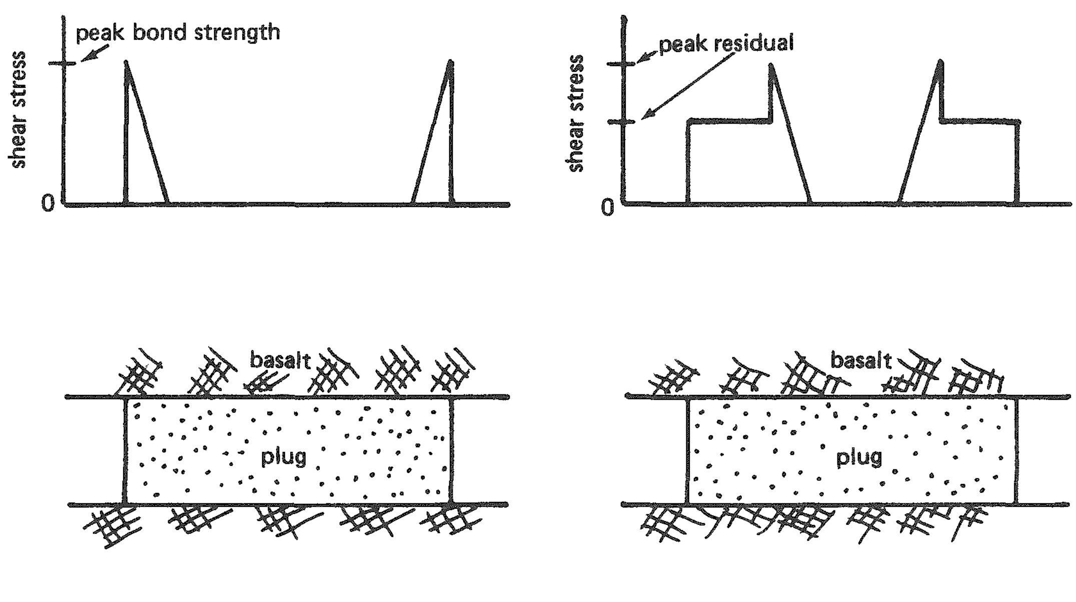
The previous sections examined the radial and tangential stresses in the plane perpendicular to the plug axis and the axial stresses in the plug. In this section the shear stresses at the plug-wall rock interface along surfaces parallel to the plug axis are studied. The plug is unconfined at each end in this discussion. The distribution of the shear stress along the plug/rock interface is non-uniform. At sections very distant from the ends of the plug, the plug is sufficiently confined by an axial stress, $\sigma_z = 2\nu P - E\alpha T$ (Equation B-10, to prevent any axial strain. Since no axial strain occurs in the basalt either, the shear stress here is zero.

Near the ends of a plug the shear stress becomes significant. The integral of the shear stress over the length of plug surface area over which it is applied ($\int_{l=0}^{\infty} \tau(l)\cdot\pi r^2 dl$) is approximately equal to $\sigma_z \cdot \pi r^2$ where $\tau(l)$ is the shear stress and is a function of distance from the plug end, σ_z is the axial stress in the center of the plug, and πr^2 is the cross-sectional area of the plug. In other words, the force that confines the plug center and keeps it from undergoing strain is provided by the shear stress over the end sections of the plug.

The shear distribution over the ends of the plug is non-uniform and will change as the plug is heated. Consider the following case. The first increment of temperature ΔT is applied. Only the unit length of plug right at the end of the plug is free to strain. Differential axial strains will develop between the plug, which is trying to expand, and the basalt which is confined and cannot strain axially. This differential axial strain causes a shear stress at the plug/rock interface. This shear stress will increase until (1) equilibrium is reached, or (2) the peak strength of the bond is exceeded over the unit plug length. In the second case, slip will then occur between the plug and the rock over the unit length, and the shear stress will be reduced to the residual or frictional value. This slip allows strain to occur in the adjacent unit length of plug, and for that unit length either (1) slip will occur, or (2) equilibrium will be reached. Eventually, shear stress will be mobilized over a sufficient plug length that the force pushing out from the center of the plug ($\sigma_z \cdot A$) will be balanced by the shear stress mobilized $\int_{l=0}^{l=\infty} \tau(l) \cdot \pi r^2 dl$.

This balanced state is the equilibrium condition.

Because the axial force in the confined section of the plug increases with temperature (Equation B-10), it can be seen that the length of plug over which the shear stress is mobilized must also increase with temperature. The sketch below suggests two simplified stress distributions. One is for the case where the first temperature increment ΔT is small enough that the peak shear is not exceeded. The stress-strain properties of the interface in shear must be determined to define this distribution properly. The second case is for a large temperature increase, where frictional bond strength controls the plug length over which shear is developed. Calculations for the second case are difficult also because the residual shear force is a function of the friction angle and the radial stress at the interface. The relationship between radial stress and longitudinal displacement in a plug where slip at the ends is allowed has not been studied.



Case 1: Small Temperature Change

Case II: Large Temperature Change

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APPENDIX C

PLUG LENGTH FOR RADIONUCLIDE BARRIER PERFORMANCE

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PLUG LENGTH FOR RADIONUCLIDE BARRIER PERFORMANCE

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PLUG LENGTH FOR RADIONUCLIDE BARRIER PERFORMANCE

Resolution of the mass transport equations in the case of the saturated, one-dimensional, half-space medium with a constant infinite source term is as follows:

C.1 EQUATIONS OF MASS TRANSPORT (from Aikens and others, 1979)

The equations of continuity for a stationary medium, without source or sink of contaminants, which is saturated and subject to reversible ion exchange processes for a radionuclide (λ), is

$$\bar{\nabla}\bar{J} + nR[\lambda C + \frac{\partial}{\partial t}C] = 0, \qquad \text{(C-1)}$$

The equation relating the concentration of a contaminant to the flux of that contaminant is

$$\bar{J} = [\bar{V} - \bar{\bar{D}}\bar{V}] \cdot [n \cdot C]. \qquad \text{(C-2)}$$

introducing Equation C-2 into Equation C-1 gives

$$\bar{J} = [\bar{V} - \bar{\bar{D}}\bar{\nabla}] \cdot [nC] \qquad \text{(C-3)}$$

where J = flux of contaminant
$\bar{\nabla}$ = gradient operator
n = effective porosity
R = retardation coefficient
λ = decay constant of the radionuclide
C = concentration of the contaminant
V = hydraulic velocity
D = dispersion coefficient (tensor).

Formulation of Equation C-3 for an undimensional model leads to

$$\left(D\frac{\partial}{\partial x^2} - V\frac{\partial}{\partial x}\right)C = R\left(\lambda C + \frac{\partial C}{\partial t}\right) \qquad \text{(C-4)}$$

where D and V are the dispersion coefficient and the hydraulic velocity, respectively, in the x direction.

Introducing the condition that the boundary at x = 0 is considered a no flow boundary for $x < 0$; therefore, the resolution of Equation C-4 leads to

$$C(x,t) = \int_0^t dt' \, C_g(x,t;o,t')\, S(t') \qquad \text{(C-5)}$$

where Cg (x,t; o,t') is the Green's Function given by

$$C_g(x,t;o,t') = -\exp\left[-\lambda(t,t') + \frac{Vx}{2D}\right] \frac{\partial}{\partial x}\left[\exp\left(\frac{Vx}{2D}\right) \operatorname{erfc}\left(\frac{x+V(t-t')}{4D(t-t')}\right)\right] \tag{C-6}$$

and where S (t') is the source distribution at the origin.

To resolve Equation C-5 for the case of a constant source point, S (t') = So 0 < t' < T (T is an arbitrary limit set to the infinity) gives:

$$C(x,t<T) = \frac{2So}{V(2+\Theta)} \exp\left(-\frac{xV\Theta}{2D}\right)\left\{E(x;t;\Theta) + \frac{\exp\left[xV(1+\Theta)/D\right]}{\Theta}\right.$$

$$\left.\left[\exp\left(-\frac{xV\Theta}{2D} - \lambda t\right)\operatorname{erfc}\left(\frac{x+Vt}{\sqrt{4Dt}}\right) - \operatorname{erfc}\left(\frac{x+Vt(1+\Theta)}{\sqrt{4Dt}}\right)\right]\right\} \tag{C-7}$$

where

$$E(x;t;\Theta) = \tfrac{1}{2}\left\{\operatorname{erfc}\left[\frac{x+Vt(1+\Theta)}{\sqrt{4Dt}}\right] - \exp\left[xV(1+\Theta)/D\right]\operatorname{erfc}\left[\frac{x+Vt(1+\Theta)}{\sqrt{4Dt}}\right]\right\}$$

$$\theta = \sqrt{1 + \frac{4\lambda DR}{V}} - 1$$

with λ = decay constant of the radionuclide
D = Dispersion coefficient
R = Retardation coefficient
V = Hydraulic velocity of the ground water.

C.2 CLOSE FORM ANALYTICAL SOLUTIONS

The concentration of each specific radionuclide is given by Equation C-6 at any time and at any distance in the plug from the plug repository interface. Because it is not possible to resolve analytically Equation C-6 it is desirable to approximate the concentration by a conservative value. The choice of a constant radioactive source term (infinite at the repository) allows to take asymptotic value when time is infinite, as a conservative value.

Analytical asymptotic values for C are given by

$$C(x=0, t=\infty) = \frac{2\,So}{V\,(2+\Theta)} \tag{C-8}$$

$$C(x=\ell, t=\infty) = \frac{2\,So}{V\,(2+\Theta)} \exp\left\{-\frac{\ell V \Theta}{2D}\right\} \tag{C-9}$$

in the numerical application C (x = 0, t = ∞) is the maximum credible concentration C_o of the corresponding radionuclide in the repository; C (x = ℓ , t = ∞) is the concentration limit C_ℓ defined by NRC regulations, eliminating So between Equations C-7, C-8, C-9. This leads to:

$$C_{\ell} = C_o \exp\left(-\frac{\ell V \Theta}{2D}\right) \qquad \text{(C-10)}$$

or with introducing $D = \alpha V$

$$\ell = \frac{2\alpha}{\Theta} \ln \frac{C_o}{C_{\ell}} \qquad \text{(C-11)}$$

where ℓ is the required length of plug; the maximum credible concentration of one specific radionuclide at the end of the plug must stay below the maximum allowable concentration stipulated by NRC regulations.

REFERENCES

Aikens, A. E., and Dames & Moore staff, 1979, Doses from ground-water migration of radionuclides in LWR waste in shallow burial trenches; 3rd revision: Prepared by Dames & Moore, San Francisco, California, for the Atomic Industrial Forum, Inc.

APPENDIX D

CALCULATION DATA FOR PLUG RADIONUCLIDE BARRIER PERFORMANCE

APPENDIX D

CALCULATION DATA FOR PLUG RADIONUCLIDE BARRIER PERFORMANCE

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LENGTH OF PLUG REQUIRED FOR VARIOUS RADIONUCLIDES, BASED ON ASSUMED VALUES OF HYDRAULIC PARAMETERS[a]

Isotope	$C\ell^b$ (μC_i)	Co^c (μC_i)	Half-life (years)	Retardation Coefficient	Θ^d	$\left(\frac{2\alpha}{\Theta}\right)^e$	ℓ (meters)
C^{14}	8×10^{-4}	3.91×10^{-3}	573×10^{3}	10	11.5	0.529	0.8
I^{129}	6×10^{-8}	1.31×10^{-4}	157×10^{7}	1	0.00284	2,147	16,507
U^{238}	4×10^{-5}	1.56×10^{-3}	451×10^{9}	14,300	0.133	45.93	168.3
Pu^{239}	5×10^{-6}	8.11×10^{2}	244×10^{4}	10,000	190	0.0320	0.6
Am^{224}	4×10^{-6}	1.87×10^{1}	458×10^{2}	10,000	1,395	0.00437	0.1
Np^{237}	3×10^{-6}	6.70×10^{-1}	216×10^{6}	100	1.27	15.80	194.6

[a] Calculations were based on the following assumed preconceptual values of hydraulic parameters:

hydraulic gradient = 10^{-3}
effective porosity of plug = 1/3
dispersivity of plug = 3.048 m
permeability of plug = 10^{-7} cm/sec.

[b] Concentration limit NRC 10 CFR 20

[c] Maximum credible concentration in the repository

[d] $\Theta = \sqrt{1 + \frac{4\lambda\alpha R}{v}} - 1$

where λ is the decay coefficient

[e] α = dispersivity

TABLE D-II

RELATIONS BETWEEN CONCENTRATION IN IODINE 129-IN REPOSITORY AND LENGTH OF PLUG FOR RETARDATION COEFFICIENT EQUALING 1, 10, AND 100 m

Concentration in the Repository ($\mu C_i/m\ell$)	Lengths of Plug (in meters) for Retardation Coefficient (R)		
	R=1	R=10	R=100
6×10^{-8}	0	0	0
7×10^{-8}	331	33.51	3.72
8×10^{-8}	618	62.55	6.95
9×10^{-8}	871	88.16	9.79
1×10^{-7}	1,097	111.1	12.34
2×10^{-7}	2,585	261.8	29.1
3×10^{-7}	3,455	350.0	38.87
5×10^{-7}	4,552	461.0	51.2
1×10^{-6}	6,040	611.7	67.9
2×10^{-6}	7,529	762.5	84.7
3×10^{-6}	8,399	850.6	94.5
5×10^{-6}	9,496	961.7	106.8
1×10^{-5}	10,984	1,112.4	123.6
2×10^{-5}	12,472	1,263.1	140.3
4×10^{-5}	13,960	1,413.8	157.0
5×10^{-5}	14,440	1,462.4	162.4
1×10^{-4}	15,928	1,613.1	179.2
2×10^{-4}	17,416	1,763.8	195.9
5×10^{-4}	19,383	1,963.1	218.0
1×10^{-3}	20,871	2,113.8	234.8
5×10^{-3}	24,327	21,163.7	273.6
1×10^{-2}	25,815	2,614.4	290.4
5×10^{-2}	29,270	2,964.4	329.2
1×10^{-1}	30,759	3,115.1	346.0
5×10^{-1}	34,214	3,465.1	384.8

TABLE D-III

RELATION BETWEEN CONCENTRATION IN REPOSITORY AND LENGTH OF PLUG FOR U_{238}, Np_{237}, I_{129}.

Concentration in the Repository ($\mu C_i/m\ell$)	Lengths of Plug (in meters)* for Retardation Coefficient (R) U^{238} R=14,300	Np^{237} R=100	I^{129} R=1
6×10^{-8}	0	0	0
7×10^{-8}	0	0	331
8×10^{-8}	0	0	618
9×10^{-8}	0	0	871
1×10^{-7}	0	0	1,097
2×10^{-7}	0	0	2,585
3×10^{-7}	0	0	3,455
5×10^{-7}	0	0	4,552
1×10^{-6}	0	0	6,040
2×10^{-6}	0	0	7,529
3×10^{-6}	0	0	8,399
5×10^{-6}	0	8.07	9,496
1×10^{-5}	0	19.02	10,984
2×10^{-5}	0	29.97	12,472
4×10^{-5}	0	40.9	13,960
5×10^{-5}	10.2	44.5	14,440
1×10^{-4}	42.1	55.4	15,928
2×10^{-4}	73.9	66.4	17,416
5×10^{-4}	116.0	80.8	19,383
1×10^{-3}	147.8	91.8	20,871
5×10^{-3}	221.8	117.2	24,327
1×10^{-2}	253.6	128.2	25,815
5×10^{-2}	327.5	153.6	29,270
1×10^{-1}	359.4	164.5	39,759
5×10^{-1}	433.3	190.0	34,214
1	465.1	200.9	35,702
10	570.9	237.3	40,646
100	676.6	273.7	45,590

* Permeability of plug: $K = 10^{-7}$ cm/sec

APPENDIX E

DESIGN FUNCTION RATING MATRICES

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DESIGN FUNCTION RATING MATRICES

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TABLE E-I

TUNNEL PLUG/WALL ROCK INTERFACE PERFORMANCE

Scheme No.	Material	Machine	Figure No.	Sliding stability	Plug/wall-rock continuity after in-situ thermo-mechanical loading	Reliability of interface joint closure during construction
	Monolithic Plug Schemes	Parameters				
T 1	75-mm maximum aggregate in stiff clay	Large compactor and small compactor	23	1	1	0
T 2	75-mm maximum aggregate in concrete	Concrete pump system	22	2	2	2
T 3	10-mm maximum aggregate in stiff clayey mixture	Portable compactor or large compactor, depending on the size of the plug	20	1	1	0
T 4	10-mm maximum aggregate in clay slurry mixture	Concrete pump system	22	0	0	2
T 5	10-mm maximum aggregate in cement mixture	Concrete pump system	22	2	2	2
T 6	Clay mixed with sand/silt	Portable or large compactor, depending on the size of the plug	20	1	1	1
T 7	Clay including pelleted bentonite mixed with sand/silt	Portable compactor	20	1	1	2
T 8	Clay mixed with sand/silt in slurry	Grout pump system	–	–	–	–
T 9	Cement mixed with sand/silt in slurry	Grout pump system	–	–	–	–
T 10	Solid inclusion of basalt	R & D system	24	?(0)	1	?(0)
T 11	Basalt block with mortared joints	Hand - masoned block	21	2	2	2
T 12	Compressed bentonite block, dry pack joint with bentonite	Hand - masoned block	21	1	2	3

TABLE E-II

TUNNEL PLUG AND DISTURBED ZONE MECHANICAL STABILITY PERFORMANCE

Scheme No.	Material	Machine	Figure No.	Plug mechanical stability under in-situ thermomechanical loading	Long-term wall support provided by plug
	Monolithic Plug Schemes	Parameters			
T 1	75-mm maximum aggregate in stiff clay	Large compactor and small compactor	23	0	0
T 2	75-mm maximum aggregate in concrete	Concrete pump system	22	1	1
T 3	10-mm maximum aggregate in stiff clayey mixture	Portable compactor or large compactor, depending on the size of the plug	20	0	0
T 4	10-mm maximum aggregate in clay slurry mixture	Concrete pump system	22	0	0
T 5	10-mm maximum aggregate in cement mixture	Concrete pump system	22	1	1
T 6	Clay mixed with sand/silt	Portable or large compactor, depending on the size of the plug	20	0	0
T 7	Clay including pelleted bentonite mixed with sand/silt	Portable compactor	20	0	0
T 8	Clay mixed with sand/silt in slurry	Grout pump system	—	—	—
T 9	Cement mixed with sand/silt in slurry	Grout pump system	—	—	—
T 10	Solid inclusion of basalt	R & D system	24	2	1
T 11	Basalt block with mortared joints	Hand - masoned block	21	1	1
T 12	Compressed bentonite block, dry pack joint with bentonite	Hand - masoned block	21	0	0

TABLE E-III

TUNNEL DISTURBED ZONE PERFORMANCE

Scheme No.	Material	Machine	Figure No.	Disturbed zone treatment performance	Construction difficulty
	Monolithic Plug Schemes / **Parameters**				
T 1	75-mm maximum aggregate in stiff clay	Large compactor and small compactor	23	0	0
T 2	75-mm maximum aggregate in concrete	Concrete pump system	22	1	1
T 3	10-mm maximum aggregate in stiff clayey mixture	Portable compactor or large compactor, depending on the size of the plug	20	1	0
T 4	10-mm maximum aggregate in clay slurry mixture	Concrete pump system	22	2	1
T 5	10-mm maximum aggregate in cement mixture	Concrete pump system	22	2	1
T 6	Clay mixed with sand/silt	Portable or large compactor, depending on the size of the plug	20	2	0
T 7	Clay including pelleted bentonite mixed with sand/silt	Portable compactor	20	2	0
T 8	Clay mixed with sand/silt in slurry	Grout pump system	22	1	2
T 9	Cement mixed with sand/silt in slurry	Grout pump system	22	1	2
T 10	Solid inclusion of basalt	R & D system	24	0	0
T 11	Basalt block with mortared joints	Hand - masoned block	21	1	1
T 12	Compressed bentonite block, dry pack joint with bentonite	Hand - masoned block	21	2	1

TABLE E-IV

TUNNEL PLUG LONG-TERM INTEGRITY

Scheme No.	Material	Machine	Figure No.	Solubility	Documented history of survival	E_h stability
	Monolithic Plug Schemes	Parameters				
T 1	75-mm maximum aggregate in stiff clay	Large compactor and small compactor	23	1	2	2
T 2	75-mm maximum aggregate in concrete	Concrete pump system	22	1	1	3
T 3	10-mm maximum aggregate in stiff clayey mixture	Portable compactor or large compactor, depending on the size of the plug	20	1	2	2
T 4	10-mm maximum aggregate in clay slurry mixture	Concrete pump system	22	1	2	2
T 5	10-mm maximum aggregate in cement mixture	Concrete pump system	22	1	1	3
T 6	Clay mixed with sand/silt	Portable or large compactor, depending on the size of the plug	20	1	2	2
T 7	Clay including pelleted bentonite mixed with sand/silt	Portable compactor	20	1	2	2
T 8	Clay mixed with sand/silt in slurry	Grout pump system	22	1	2	2
T 9	Cement mixed with sand/silt in slurry	Grout pump system	22	1	1	3
T 10	Solid inclusion of basalt	R & D system	24	1	2	2
T 11	Basalt block with mortared joints	Hand - masoned block	21	1	1	2
T 12	Compressed bentonite block, dry pack joint with bentonite	Hand - masoned block	21	1	2	2

TABLE E-V
SHAFT CORE BARRIER PERFORMANCE

Monolithic Plug Schemes / Parameters							
Scheme No	Material	Machine	Figure No	Ion exchange	Permeability	Uniformity	Unit cost
S 1	75-mm maximum aggregate in concrete	Concrete wireline system	17	0	1	2	1
S 2	75-mm maximum aggregate in concrete	Concrete pump system	18	0	1	2	1
S 3	10-mm maximum aggregate in stiff clayey mixture	Small compactor	16	1	2	2	2
S 4	10-mm maximum aggregate in cement mixture	Concrete wireline system	17	0	2	2	1
S 5	10-mm maximum aggregate in cement mixture	Concrete pump system	18	0	2	2	1
S 6	Clay mixed with sand/silt	Small compactor	16	2	3	2	2
S 7	Clay including pelleted bentonite mixed with sand/silt	Small compactor	16	2	3	2	2
S 8	Clay mixed with sand/silt in slurry	Concrete pump system	18	2	2	2	1
S 9	Solid inclusion of basalt	R & D system	24	0	3	2	0
S 10	Basalt block with mortared joints	Hand-masoned block	21	0	2	2	1
S 11	Compressed bentonite block, dry pack joint with bentonite	Hand-masoned block	21	2	3	2	1
S 12	Cement slurry	Concrete pump system	18	0	1	2	1

TABLE E-VI

SHAFT PLUG/WALL ROCK INTERFACE PERFORMANCE

Scheme No.	Material (Monolithic Plug Schemes)	Machine	Figure No.	Sliding Stability	Plug wall rock continuity after in-situ thermomechanical loading	Reliability of interface joint closure during construction
S 1	75-mm maximum aggregate in concrete	Concrete wireline system	17	2	3	2
S 2	75-mm maximum aggregate in concrete	Concrete pump system	18	2	3	2
S 3	10-mm maximum aggregate in stiff clayey mixture	Small compactor	16	1	3	2
S 4	10-mm maximum aggregate in cement mixture	Concrete wireline system	17	2	3	2
S 5	10-mm maximum aggregate in cement mixture	Concrete pump system	18	2	3	2
S 6	Clay mixed with sand/silt	Small compactor	16	1	3	3
S 7	Clay including pelleted bentonite mixed with sand/silt	Small compactor	16	1	3	3
S 8	Clay mixed with sand/silt in slurry	Concrete pump system	18	0	2	3
S 9	Solid inclusion of basalt	R & D system	24	?(0)	3	?(0)
S 10	Basalt block with mortared joints	Hand-masoned block	21	2	3	2
S 11	Compressed bentonite block, dry pack joint with bentonite	Hand-masoned block	21	1	3	3
S 12	Cement slurry	Concrete pump system	18	2	2	3

TABLE E-VII

SHAFT DISTURBED ZONE PERFORMANCE

Scheme No.	Monolithic Plug Schemes / Material	Machine	Figure No.	Parameters: Long-term wall rock support provided by plug material	Disturbed zone treatment performance	Construction difficulty
S 1	75-mm maximum aggregate in concrete	Concrete wireline system	17	1	1	2
S 2	75-mm maximum aggregate in concrete	Concrete pump system	18	1	1	2
S 3	10-mm maximum aggregate in stiff clayey mixture	Small compactor	16	1	1	1
S 4	10-mm maximum aggregate in cement mixture	Concrete wireline system	17	2	2	2
S 5	10-mm maximum aggregate in cement mixture	Concrete pump system	18	2	2	2
S 6	Clay mixed with sand/silt	Small compactor	16	1	2	1
S 7	Clay including pelleted bentonite mixed with sand/silt	Small compactor	16	1	2	1
S 8	Clay mixed with sand/silt in slurry	Concrete pump system	18	0	2	2
S 9	Solid inclusion of basalt	R & D system	24	1	0	0
S 10	Basalt block with mortared joints	Hand-masoned block	21	1	1	2
S 11	Compressed bentonite block, dry pack joint with bentonite	Hand-masoned block	21	1	3	2
S 12	Cement slurry	Concrete pump system	18	1	1	2

TABLE E-VIII

SHAFT PLUG LONG-TERM INTEGRITY PERFORMANCE

Scheme No.	Material (Monolithic Plug Schemes)	Machine	Figure No.	Solubility	Documented history of survival	E_h stability
S 1	75-mm maximum aggregate in concrete	Concrete wireline system	17	1	1	3
S 2	75-mm maximum aggregate in concrete	Concrete pump system	18	1	1	3
S 3	10-mm maximum aggregate in stiff clayey mixture	Small compactor	16	1	2	2
S 4	10-mm maximum aggregate in cement mixture	Concrete wireline system	17	1	1	3
S 5	10-mm maximum aggregate in cement mixture	Concrete pump system	18	1	1	3
S 6	Clay mixed with sand/silt	Small compactor	16	1	2	3
S 7	Clay including pelleted bentonite mixed with sand/silt	Small compactor	16	1	2	2
S 8	Clay mixed with sand/silt in slurry	Concrete pump system	18	1	2	2
S 9	Solid inclusion of basalt	R & D system	24	1	2	2
S 10	Basalt block with mortared joints	Hand-masoned block	21	1	1	2
S 11	Compressed bentonite block, dry pack joint with bentonite	Hand-masoned block	21	1	2	2
S 12	Cement slurry	Concrete pump system	18	1	1	3

TABLE E-IX

BOREHOLE PLUG FROM SURFACE CORE BARRIER PERFORMANCE

Scheme No	Material	Machine	Figure No	Ion exchange	Permeability	Uniformity	Cost
	Monolithic Plug Schemes	Parameters					
B 1	10-mm maximum aggregate in stiff clayey mixture	R & D system	12	1	2	1	0
B 2	10-mm maximum aggregate in slurry clay mixture	Grouting system	9	1	1	1	2
B 3	10-mm maximum aggregate in cement mixture	Grouting system	9	0	2	1	2
B 4	Clay mixed with sand and silt	R & D system	12	2	2	1	0
B 5	Clay mixed with sand and silt in slurry	Grouting system	9	2	1	2	2
B 6	Cement slurry	Grouting system	9	0	2	1	2
B 7	Basalt solid inclusion	R & D system	14	0	3	2	0
B 8	10-mm aggregate with clay in bentonite slurry	R & D system	11	1	2	2	2
B 9	10-mm aggregate with bentonite pellets in clay slurry	Gravel pack plant	10	1	2	2	2

TABLE E-X

BOREHOLE PLUG FROM SURFACE WALL ROCK INTERFACE PERFORMANCE

Scheme No.	Material	Machine	Figure No.	Sliding stability	Plug wall rock continuity after thermomechanical loading	Reliability of interface joint closure during construction
	Monolithic Plug Schemes	Parameters				
B 1	10-mm maximum aggregate in stiff clayey mixture	R & D system	12	1	3	0
B 2	10-mm maximum aggregate in slurry clay mixture	Grouting system	9	0	2	2
B 3	10-mm maximum aggregate in cement mixture	Grouting system	9	2	3	2
B 4	Clay mixed with sand and silt	R & D system	12	1	3	0
B 5	Clay mixed with sand and silt in slurry	Grouting system	9	1	2	2
B 6	Cement slurry	Grouting system	9	2	3	3
B 7	Basalt solid inclusion	R & D system	14	?(0)	?3	?(0)
B 8	10-mm aggregate with clay in bentonite slurry	R & D system	11	0	3	3
B 9	10-mm aggregate with bentonite pellets in clay slurry	Gravel pack plant	10	0	3	3

TABLE E-XI

BOREHOLE PLUG FORM SURFACE LONG-TERM INTEGRITY

Monolithic Plug Schemes				Parameters		
Scheme No.	Material	Machine	Figure No.	Solubility	Documented history of survival	E_h stability
B 1	10-mm maximum aggregate in stiff clayey mixture	R & D system	12	1	2	2
B 2	10-mm maximum aggregate in slurry clay mixture	Grouting system	9	1	2	2
B 3	10-mm maximum aggregate in cement mixture	Grouting system	9	1	1	3
B 4	Clay mixed with sand and silt	R & D system	12	1	2	2
B 5	Clay mixed with sand and silt in slurry	Grouting system	9	1	2	2
B 6	Cement slurry	Grouting system	9	1	1	3
B 7	Basalt solid inclusion	R & D system	14	1	2	2
B 8	10-mm aggregate with clay in bentonite slurry	R & D system	11	1	2	2
B 9	10-mm aggregate with bentonite pellets in clay slurry	Gravel pack plant	10	1	2	2

APPENDIX F

EXTENDED DOMINANCE ANALYSIS
OF MONOLITHIC PLUG SCHEMES

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EXTENDED DOMINANCE ANALYSIS OF MONOLITHIC PLUG SCHEMES

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APPENDIX F

EXTENDED DOMINANCE ANALYSIS OF MONOLITHIC PLUG SCHEMES

F.1 INTRODUCTION

The purpose of the extended dominance analysis is to help support a basis for priority of further study of monolithic plug scheme alternatives. None of the alternatives are completely defined as yet, so that a definitive ranking is not really feasible. It is likely that as the alternatives are studied further, their apparent desirability will change. Some comment about limitations in the use of this type of analysis is necessary. Remember that all of the results of the dominance analysis are ordinal. That is, no information is given about how much more or less desirable an alternative in one group is than an alternative in another. For instance, the alternatives in Group A could either be greatly or infinitesimally more desirable than those in Group B. Similarly, one should not attempt to order the alternatives within each group by the number of times they are dominated.

This information is important, but it only applies to the specific relationship between the undominated and dominated alternatives. It is possible for a dominated alternative to be more desirable than an undominated alternative under certain ranking schemes. In general, the alternatives should be examined on an individual basis before selecting them for further study in either a monolithic or multi-zone plug system. The information presented here should only serve as a guide in making those selections.

The next section will show a detailed example of how the dominance analysis calculations were done and summaries of the remaining calculations are given.

F.2 COMPUTATIONAL EXAMPLE

This section describes the application of the extended dominance methodology. The evaluation of the plug performance category for tunnels is described.

For tunnels, plug performance has four evaluation measures; X_1: uniformity, X_2: permeability, X_3: ion exchange capacity, X_4: cost. These measures all had scales of potential performance ranging from 0 to 2 so no normalization was necessary. It was decided that four constraints were appropriate.

$$K_1 > K_3$$
$$K_2 > K_3$$
$$K_1 > K_4$$
$$K_2 > K_4$$

where

K_1 = The scaling constant for uniformity
K_2 = The scaling constant for permeability
K_3 = The scaling constant for ion exchange capacity
K_4 = The scaling constant for cost

and

$$K_1 + K_2 + K_3 + K_4 = 1.$$

Intuitively, this implies that uniformity and permeability are "more important than" cost and ion exchange capacity. Using the technique described in Appendix B, five variables were used in the dominance calculations:

$$Y_1 = X_1$$
$$Y_2 = X_2$$
$$Y_3 = X_1 + X_2 + X_3$$
$$Y_4 = X_1 + X_2 + X_4$$
$$Y_5 = X_1 + X_2 + X_3 + X_4.$$

These variables correspond to the five feasible extreme points (K_1=1, K_2=1, K_1=K_1=K_2=K_3=1/3, K_1=K_2=K_4=1/3, K_1=K_2=K_3=K_4=1/4) for the equation $V = K_1\ V_1\ (X_1) + K_2\ V_2\ (X_2) + K_3\ V_3\ (X_3) + K_4\ V_4\ (X_4)$.

The values for these variables are shown in Table F-I. The results of the dominance calculation (done by computer) are shown in a dominance matrix (Table F-II). The grouping is calculated in Table F-III.

Based on Table F-III, the alternatives can be divided into three groups:

Group A: Alternatives not dominated;
Group B: Alternatives dominated one to eight times;
Group C: Alternatives dominated nine times.

By examining the columns of the matrix in Table F-II, the groups are:

Group A: T12
Group B: T2, T3, T4, T5, T6, T7, T10, T11
Group C: T1.

TABLE F-I

SUMMARY OF TUNNEL CORE BARRIER
PERFORMANCE VARIABLES
FOR DOMINANCE ANALYSIS

ALTERNATIVE	X_1	X_2	X_3	X_4	Y_1*	Y_2*	Y_3*	Y_4*	Y_5*
T1	0	0	1	2	0	0	1	2	3
T2	2	0	0	1	2	0	1	2	3
T3	1	1	1	2	1	1	3	4	5
T4	2	1	1	1	2	1	4	4	5
T5	2	1	0	1	2	1	3	4	4
T6	1	2	2	2	1	2	5	5	7
T7	1	2	2	2	1	2	5	5	7
T8	-	-	-	-	-	-	-	-	-
T9	-	-	-	-	-	-	-	-	-
T10	2	2	0	0	2	2	4	4	4
T11	2	1	0	1	2	1	3	4	4
T12	2	2	2	1	2	2	6	5	7

*$Y_1 = X_1$;
$Y_2 = X_2$;
$Y_3 = X_1 + X_2 + X_3$;
$Y_4 = X_1 + X_2 + X_4$;
$Y_5 = X_1 + X_2 + X_3 + X_4$

TABLE F-II

DOMINANCE ANALYSIS
RESULTS FOR TUNNEL
CORE BARRIER
PERFORMANCE

ALTERNATIVE	T 1	T 2	T 3	T 4	T 5	T 6	T 7	T[a] 8	T[a] 9	T 10	T 11	T 12
T1												
T2	1[b]											
T3	1											
T4	1	1	1		1						1	
T5	1	1										
T6	1		1									
T7	1		1									
T8[a]												
T9[a]												
T10	1				1						1	
T11	1	1										
T12	1	1	1	1	1	1	1			1	1	
TOTALS	9	5	4	1	3	1	1			1	3	

[a]Not evaluated

[b]"Row" alternative dominates the "Column" alternative

TABLE F-III

DOMINANCE MATRIX

Number Needed	Number of Times Dominated	Number of Occurrences	Cumulative Occurrences
1	9	1	1
2	8	0	1
3	7	0	1
4	6	0	1
5	5	1	2
6	4	1	2
7	3	2	5
8	2	0	5
9	1	4	9
10	0	1	10

NOTE: When the number needed matches the cumulative number of occurances, a line is drawn below that row. This indicates that the alternatives.

Here, Group B is very large. However, certain statements can be made about the ordering of alternatives within this group. By studying Table F-II, alternatives T4, T5, T10, and T11 all dominate T2 in Group B. Alternatives T3, T5, and T11 are also dominated in the group. When selecting alternatives from Group B, this dominance information should be kept in mind. Table F-IV summarizes the results of the dominance analysis for core barrier performance.

F.3 RESULTS OF EXTENDED DOMINANCE ANALYSIS

The type of analysis described above was done for all of the categories related to shafts, boreholes, and tunnels. The assumptions made and the results obtained are discussed in this section.

F.3.1 Shafts

Evaluations of shaft alternatives were based on five categories: (1) Core Barrier Performance, (2) Plug/Wall-Rock Interface, (3) Support, (4) Disturbed Zone, and (5) Long-Term Effects.

(1) Core Barrier Performance was measured on the basis of permeability cost and ion exchange potential. Two further assumptions were made:

$$K\ (\text{permeability}) > K\ (\text{cost})$$
$$K\ (\text{permeability}) > K\ (\text{ion exchange})$$

where K(X) is the scaling constant associated with measure X, if an additive preference function is assumed. These

TABLE F-IV

TUNNEL DOMINANCE ANALYSIS

CATEGORY 1: CORE BARRIER PERFORMANCE

Alternative	Group	Choose These First
T 1	C	-
T 2	B	4,5,10,11
T 3	B	4,6,7
T 4	B	-
T 5	B	4,10
T 6	B	-
T 7	B	-
T 8	-	-
T 9	-	-
T10	B	-
T11	B	4,10
T12	A	-

assumptions require that the dominance calculation be done on four variables:

Permeability
Permeability + cost
Permeability + ion exchange potential
Permeability + cost + ion exchange potential.

The five groups resulting from this calculation are shown in Table F-V.

(2) Plug/Wall Rock Interface was evaluated on the basis of sliding stability, continuity after thermomechanical loading, and reliability of joint closure during construction. It was assumed that:

K (thermomechanical) > K (sliding stability)
and
K(construction) > K (sliding stability).

This implied the use of three variables in the dominance computation

- Thermomechanical
- Construction
- Thermomechanical + construction + sliding stability.

The results are shown in Table F-VI.

(3) Support was based on the single variable, long-term wall rock support. Thus, each level of this variable resulted in a different group. The results are shown in Table F-VII.

TABLE F-V

SHAFT DOMINANCE ANALYSIS

CATEGORY 1: CORE BARRIER PERFORMANCE

Alternative	Group	Choose These First
1	E	-
2	E	-
3	C	-
4	D	-
5	D	-
6	A	-
7	A	-
8	-	-
9	C	-
10	D	-
11	B	-
12	B	-
13	-	-
14	E	-

TABLE F-VI

SHAFT DOMINANCE ANALYSIS

CATEGORY 2: PLUG/WALL-ROCK INTERFACE

Alternative	Group	Choose These First
S1	A	-
S2	A	-
S3	A	1,2,4,5,6,7,11,12
S4	A	-
S5	A	-
S6	A	-
S7	A	-
S8	A	6,7,14
S9	A	1,2,3,11,4,5,6,7,12
S10	A	-
S11	A	-
S12	A	-

TABLE F-VII

SHAFT DOMINANCE ANALYSIS

CATEGORY 3: SUPPORT

Alternative	Group	Choose These First
S1	B	-
S2	B	-
S3	B	-
S4	A	-
S5	A	-
S6	B	-
S7	B	-
S8	B	-
S9	C	-
S10	B	-
S11	B	-
S12	B	-

(4) Disturbed Zone considerations used two variables: disturbed zone performance and construction difficulty. No further assumptions were made. The five resulting groups are shown in Table F-VIII.

(5) Long-Term Integrity was measured using documented history of survival and Eh stability. It was assumed that K (history) > K (Eh), implying the use of two variables in the dominance computations: history and history plus Eh

The resulting three groups are shown in Table F-IX. The results of all dominance analyses for shafts are summarized in Table F-X.

F.3.2 Tunnels

Tunnels were evaluated on the basis of five categories: (1) Core Barrier Performance, (2) Plug/Wall-rock Interface, (3) Disturbed Zone, (4) Mechanical Stability, and (5) Long-Term Effects.

(1) Core Barrier Performance used the measure of uniformity, in addition to those used for shafts. (The shaft alternatives did not differ significantly in uniformity.) Two additional assumptions were made:

K (uniformity) > K (cost)
K (uniformity) > K (ion exchange potential).

Five variables were required for the dominance computation:

- Permeability
- Uniformity

TABLE F-VIII

SHAFT DOMINANCE ANALYSIS

CATEGORY 4: DISTURBED ZONE

Alternative	Group	Choose These First
S1	C	-
S2	C	-
S3	D	-
S4	B	-
S5	B	-
S6	C	-
S7	C	-
S8	B	-
S9	E	-
S10	C	-
S11	A	-
S12	C	-

TABLE F-IX

SHAFT DOMINANCE ANALYSIS

CATEGORY 5: LONG-TERM EFFECTS

Alternative	Group	Choose These First
S1	B	-
S2	B	-
S3	A	-
S4	B	-
S5	B	-
S6	A	-
S7	A	-
S8	A	-
S9	A	-
S10	C	-
S11	A	-
S11	B	-

TABLE F-X

SUMMARY OF DOMINANCE COMPUTATIONS FOR SHAFTS

ALTERNATIVE		PERFORMANCE	PLUG/WALL-ROCK INTERFACE	SUPPORT	DISTURBED ZONE	LONG TERM
S1	12	E	A	B	C	B
S2	12	E	A	B	C	B
S3	14	C	A (8)	B	D	A
S4	15	D	A	A	B	B
S5	15	D	A	A	B	B
S6	o 17	A	A	B	C	A
S7	o 17	A	A	B	C	A
S8		-	-	-	-	-
S9	16	C	A (4)	B	B	A
S10	12	C	A (9)	C	E	A
S11	12	D	A	B	C	C
S12	o 18	B	A	B	A	A
S13		-	-	-	-	-
S14	12	E	A	B	C	B

- Permeability + uniformity + cost
- Permeability + uniformity + ion exchange
- Permeability + uniformity + ion exchange + cost.

The results are shown in Table F-IV.

(2) Plug/Wall-Rock Interface used the same three variables as shafts, but no assumptions were made about their relative importance. The results are shown in Table F-XI.

(3) Disturbed Zone used the same variables and assumptions as used for shafts. The results are shown in Table F-XII.

(4) Mechanical Stability included the support variable used for shafts and the variable mechanical stability under thermo-mechanical coding. No assumptions about relative importance were made. The results are shown in Table F-XIII.

(5) Long-Term Effects were analyzed in the same way as for shafts; the results are shown in Table F-XIV.

The results of all dominance analyses for tunnels are shown in Table F-XV.

F.3.3 Boreholes

Boreholes were evaluated for three categories: (1) Core Barrier Performance, (2) Plug/Wall-Rock Interface, and (3) Long-Term Effects.

TABLE F-XI

TUNNEL DOMINANCE ANALYSIS

CATEGORY 2: PLUG/WALL-ROCK INTERFACE

Alternative	Group	Choose These First
T1	C	6
T2	A	-
T3	C	6
T4	C	-
T5	A	-
T6	C	-
T7	B	-
T8	-	-
T9	-	-
T10	C	1,3,6
T11	A	-
T12	A	-

TABLE F-XII

TUNNEL DOMINANCE ANALYSIS

CATEGORY 3: DISTURBED ZONE

Alternative	Group	Choose These First
T1	C	-
T2	A	4,5,8,9,12
T3	B	-
T4	A	-
T5	A	-
T6	A	4,5,12
T7	A	4,5,12
T8	A	-
T9	A	-
T10	C	-
T11	A	4,5,8,9,12
T12	A	-

TABLE F-XIII

TUNNEL DOMINANCE ANALYSIS

CATEGORY 4: MECHANICAL STABILITY

Alternative	Group	Choose These First
T1	C	-
T2	B	-
T3	C	-
T4	C	-
T5	B	-
T6	C	-
T7	C	-
T8	-	-
T9	-	-
T10	A	-
T11	B	-
T12	C	-

TABLE F-XIV

TUNNEL DOMINANCE ANALYSIS

CATEGORY 5: LONG-TERM EFFECTS

Alternative	Group	Choose These First
T1	A	-
T2	B	-
T3	A	-
T4	A	-
T5	B	-
T6	A	-
T7	A	-
T8	A	-
T9	B	-
T10	A	-
T11	C	-
T12	A	-

TABLE F-XV

SUMMARY OF DOMINANCE ANALYSIS RESULTS FOR TUNNELS

ALTERNATIVE			PERFORMANCE	PLUG/WALL-ROCK INTERFACE	SUPPORT	DISTURBED ZONE	LONG TERM
T1	2	o	C	C (1)	C	C	A
T2	7	o	B (4)	A	B	A (5)	B
T3	4		B (3)	C (1)	C	B	A
T4	5		B	C	C	A	A
T5	7	o	B (2)	A	B	A	B
T6	5		B	C	C	A (3)	A
T7	6	o	B	B	C	A (3)	A
T8			-	-	-	A	A
T9			-	-	-	A	A
T10	5		B	C	A	C	A
T11	6	o	B (2)	A	B	A (5)	C
T12	8	o	A	A	C	A	A

(1) Core Barrier Performance was measured using the same variables and assumptions as for tunnels; the results are shown in Table F-XVI.

(2) Plug/Wall-Rock Interface was measured using the same variables and assumptions as for shafts; the results are shown in Table F-XVII.

(3) Long-Term Effects were also measured using the same variables and assumptions as for shafts; the results are shown in Table F-XVIII.

The results of all dominance analyses for boreholes are summarized in Table F-XIX.

TABLE F-XVI

BOREHOLE DOMINANCE ANALYSIS

CATEGORY 1: CORE BARRIER PERFORMANCE

Alternative	Group	Choose These First
B1	A	3,4,7,8,9
B2	A	3,5,6,7,8,9
B3	A	7,8,9
B4	A	7,8,9
B5	A	8,9
B6	A	3,7,8,9
B7	A	-
B8	A	-
B9	A	-

TABLE F-XVII

BOREHOLE DOMINANCE ANALYSIS

CATEGORY 2: PLUG/WALL-ROCK INTERFACE

Alternative	Group	Choose These First
B1	C	-
B2	C	5
B3	B	-
B4	C	-
B5	C	-
B6	A	-
B7	C	1,4
B8	B	-
B9	B	-

TABLE F-XVIII

BOREHOLE DOMINANCE ANALYSIS

CATEGORY 3: LONG-TERM STABILITY

Alternative	Group	Choose These First
B1	A	-
B2	A	-
B3	B	-
B4	A	-
B5	A	-
B6	B	-
B7	A	-
B8	A	-
B9	A	-

TABLE F-XIX

SUMMARY OF DOMINANCE COMPUTATIONS FOR BOREHOLES

ALTERNATIVE		PERFORMANCE	PLUG/WALL-ROCK INTERFACE	LONG-TERM EFFECTS	
B1	4	A (5)	C	A	
B2	4	A (6)	C (1)	A	
B3	4	A (3)	B	B	
B4	4	A (3)	C	A	
B5	4	A (2)	C	A	
B6	o 5	A (4)	A	B	Cement Grout
B7	4	A	C (2)	A	
B8	o 5	A	B	A	
B9	o 5	A	B	A	Bentonite Pellets Tremie

APPENDIX G

EXPERT EVALUATION FORMS AND RESULTS

APPENDIX G

EXPERT EVALUATION FORMS AND RESULTS

TABLE OF CONTENTS

LIST OF TABLES

PLUG EVALUATION FORM

PLUG TYPE ☐ Shaft ☐ Tunnel ☐ Borehole ☐ Monolithic Scheme ☐ Multiple Scheme

PLUG SCHEME NO. ____________

EVALUATOR ____________ DATE ____________

PART A: CONSIDER POTENTIAL FOR FLOW THROUGH PLUG

1. The primary function of the plug is to prevent excessive flow across the plug. Considering plug material properties and the placement techniques proposed, what is your best estimate of plug permeability? (See Notes below) Consider the likely loading conditions and environment.

NOTE 1: Ignore, for the present, flow through the surrounding rock and plug-rock interface.

NOTE 2: Consider plug permeability in its "as-placed" condition shortly after installment. Potential for deterioration over time is considered separately below.

NOTE 3: Your answer should be such that the actual permeability can be higher or lower with equal probability.

NOTE 4: (Applicable to multiple schemes only) It is understood that various plug material may have different permeabilities. Your response should give the "average" or "equivalent" plug permeability.

NOTE 5: It is recognized that different plug layers (e.g., top vs. bottom) may differ in permeability. In such cases, the highest permeability should be considered.

☐ A Low: Less than 10^{-8} cm/sec

☐ B Moderate: Between 10^{-6} to 10^{-8} cm/sec

☐ C High. More than 10^{-6} cm/sec

2. It is recognized that responding to question (1) (above) is difficult because of imperfect/limited information on some components, untested techniques/machinery and conceptual design. Express your level of confidence in your response to question (1).

☐ A High degree of confidence: Expect the true plug permeability to be very close to that estimated in (1).
☐ B Moderate degree of confidence:
☐ C Low degree of confidence: Uncertain about estimate in (1).

3. Some of the plug placement techniques/machinery may seem exotic and unproven or may be difficult/expensive to use. Express your views on degree of construction difficulties that might be expected in placing the plug as described in the scheme.

☐ A Expect no difficulties: Comfortable about technique/machinery.
☐ B Potential for some minor difficulties.
☐ C Expect some difficulties, potential for major problems. Unsure about some aspects of the procedure/technique.

4. The ideal plug material should sustain its physical/chemical characteristics over long periods of time. Does the plug material under consideration here possess such long-lived properties?

☐ A Expect no changes (i.e., no deterioration in plug material properties).
☐ B Potential for minor and gradual deterioration.
☐ C Expect some deterioration over time, potential for major problems.

5. It is recognized that concentration of most radionuclides are reduced as they migrate through plug material. Some radionuclides are more readily retained than others. Using some "average retention index", rate the plug material in terms of their overall radionuclide adsorptive/retentive properties.

☐ A High: Plug material(s) have "good" radionuclide retention properties.
☐ B Moderate: Plug material(s) have "fair" radionuclide retention properties.
☐ C Low: Plug material(s) have "poor" radionuclide retention properties.

PLUG EVALUATION FORM (Continued)

PART B: CONSIDER POTENTIAL FOR FLOW THROUGH SURROUNDING ROCK

1. It is recognized that some seepage may take place through the disturbed rock surrounding the plug. To reduce this flow, certain special features are specified in the plug system. Given these features, what is your best estimate of permeability through the disturbed rock? If no special features are specified, assume contact grouting of the surrounding disturbed rock. See Notes below.

NOTE 1: Your answer should be specifically directed to permeability through the disturbed rock surrounding the plug, including cut offs, if any.

NOTE 2: Consider permeability in its "as-placed" condition shortly after installment. Potential for deterioration over time is considered spearately below.

NOTE 3 Your answer should be such that the actual permeability can be higher or lower with equal probability.

NOTE 4: Your answer should be an "average" or "equivalent" permeability for the most likely flow path through the disturbed rock or the one with highest permeability.

☐ A Low: Less than 10^{-8} cm/sec
☐ B Moderate. Between 10^{-6} to 10^{-8} cm/sec
☐ C High: More than 10^{-6} cm/sec

2. Same as question (2) for flow through the plug (PART A).

☐ A High degree of confidence: Quite sure of response to question (1).
☐ B Moderate degree of confidence
☐ C Low degree of confidence: Uncertain about response to question (1).

3. Some of the techniques proposed to inhibit flow through disturbed rock may seem exotic and unproven or may be difficult/expensive to use. Express your views on degree of construction difficulties that might be encountered in using the scheme shown.

☐ A Expect no difficulties.
☐ B Potential for some minor difficulties.
☐ C Expect some difficulties, potential for major problems.

4. The ideal grout material or material used to fill the cut offs, if any, should sustain its physical/chemical characteristics over long periods of time. Does the material proposed for the scheme under consideration here possess such long-lived properties? Answer this question assuming Bentonite is used for grouting (Case I) or Portland Cement (Case II).

CASE I: Assume Bentonite is Used for Grouting.

☐ A Expect no deterioration in properties.
☐ B Potential for minor and gradual deterioration in properties.
☐ C Expect some deterioration over time. Potential for major problems.

CASE II: Assume Portland Cement is Used for Grouting.

☐ A
☐ B Same as Above.
☐ C

5. It is recognized that concentration of most radionuclides decreases as they migrate through the disturbed zone and cut offs, if any. Some radionuclides are more easily retained than others. Using some "average retention index", rate the disturbed zone plus any cut offs or other special features in terms of their overall radionuclide adsorptive/retention properties.

☐ A High: The system as proposed has "good" radionuclide retention properties.
☐ B Moderate: The system as proposed as "fair" radionuclide retention properties
☐ C Low: The system as proposed as "poor" radionuclide retention properties.

PLUG EVALUATION FORM (Continued)

PART C: CONSIDER POTENTIAL FOR FLOW THRU PLUG-ROCK INTERFACE DUE TO BONDING IMPERFECTIONS OR AXIAL AND RADIAL STRESSES

1. A major source of concern is potential for flow through the plug-rock interface because of imperfections such as voids, poor compaction around the plug perimeter and so on. Evaluate potential for such imperfections in the plug system shown.

- ☐ A Low: There is virtually no possibility of such imperfections in the plug system shown.
- ☐ B Moderate: There is a small possibility for such imperfections but their consequence is expected to be non-critical.
- ☐ C High: There is some possibility for such imperfections and their consequence may be serious.

2. A second source of concern is potential for flow through the plug-rock interface because of thermal incompatibilities in the plug-rock material. These incompatibilities could result because of increases or decreases in ambient temperature. Evaluate potential for such roblems in the plug system shown.

- ☐ A Low: There is a low potential for such thermal-related problems in the plug scheme shown.
- ☐ B Moderate: There is a possibility for some major plug-rock thermal incompatibility but the consequence is expected to be slight on overall plug system performance.
- ☐ C High: There is some possibility for plug-rock thermal incompatibility and its consequence may be serious.

3. In addition, there is some concern that the plug system may fail or perform poorly under transient and/or static axial and/or radial loads. In your judgement, what is the potential for such problems in the plug system shown?

- ☐ A Low: There is a low potential for such problems and the consequences are expected to be slight.
- ☐ B Moderate: There is a small possibility that the plug system may perform poorly under certain axial and/or radial loading conditions but this will not affect the system's overall performance in a major way.
- ☐ C High: There is some possibility for poor performance under certain axial and/or radial stresses and its consequence may be serious.

4. Because of its long expected life, the plug system may be subjected to dynamic loads resulting from earthquakes and other tectonic events. Assuming these events cause cyclic accelerations not exceeding 1G and differential displacements no more than 1" in 10', which may be temporary or permanent, how do you expect the plug scheme to perform?

- ☐ A Expect to perform adequately
- ☐ B Small potential for moderate damage. Should not affect plug system's overall performance in a major way.
- ☐ C Expect potential for serious damage adversely affecting system's overall performance.

5. Same as question (4) for flow through plug (PART A), except that the question applies to time dependent properties related to plug-rock interface.

- ☐ A Expect no deterioration in properties.
- ☐ B Potential for minor and gradual deterioration in properties.
- ☐ C Expect some deterioration over time. Potential for major problems.

PLUG EVALUATION FORM (Continued)

PART D: COMMENT ON THE PROPOSED SCHEME

- In Your Judgement, what are the major strengths of the proposed scheme?

____

____

____

- In Your Judgement, what are the major weaknesses of the proposed scheme?

____

____

____

- Do You have any suggestions for improving or eliminating these weaknesses?

____

____

____

- Taking Everything Into Consideration, how would you rate the proposed scheme?

☐ Very Attractive
☐ Moderately Attractive
☐ Fair
☐ Reservations

- Could You briefly comment on your rating choice (i.e., what made you choose the rating you selected)?

____

____

____

____

____

____

____

TABLE G-I

EVALUATION RESULTS: BOREHOLES

		Evaluator 1 Heavy Construction Specialist			Evaluator 2 Civil Eng. Design Specialist			Evaluator 3 Geology Specialist		
Scheme[a]	Question	Part A	Part B	Part C	Part A	Part B	Part C	Part A	Part B	Part C
1 Monolithic	1	A	A	A	B	B	B	B	A	A
	2	A	A	A	A	A	B	B	B	B
	3	A	A	A	A	A	B	A	A	A
	4	A	A/NA	A	A/B	A/B	B/C	B	NA/B	A
	5[b]	B	B	A	B	B	B	B	B	B
	Overall Rating		A			B			A	
2 Monolithic	1	B	A	B	C	B	B	B	B	B
	2	A	B	A	C	B	A	B	B	A
	3	C	A	A	B	NA	A	C	A	A
	4	A	A/A	A	B	NA	B	B	B/NA	A
	5[b]	A	B	A	A	B	B	A	B	B
	Overall Rating		C			B			A	
3 Monolithic	1	A	B	B	B	B	A	A	B	A
	2	A	C	A	B	B	A	B	B	B
	3	C	B	B	B	NA	A	B	A	A
	4	A	NA	A	B	NA	B	B	A/NA	A
	5[b]	B	B	A	B	B	B	B	B	B
	Overall Rating		B			B			A	
4 Multiple	1	A	A	B	C	C	C	A	B	C
	2	A	B	B	C	A	C	C	B	B
	3	C	A	A	C	C	B	C	B	A
	4	A	NA	A	C	NA	B	B	B/B	B
	5[b]	B	B	A	B	B	B	B	B	B
	Overall Rating		B			D			C	
5 Multiple	1	A	A	B	A	A	B	B	B	B
	2	A	B	A	A	A	B	C	B	B
	3	C	A	A	A	A	A	B	B	A
	4	A	NA	A	B	NA	B	B	NA/B	A
	5	B	B	A	B	B	B	B	B	A
	Overall Rating		B			A			C	

[a] See Table XVII

[b] Evaluations on questions A5 and B5 were done by a geochemist

TABLE G-II

EVALUATION RESULTS: TUNNELS

Scheme[a]	Question	Evaluator 1 Heavy Construction Specialist Part A	Part B	Part C	Evaluator 2 Civil Eng. Design Specialist Part A	Part B	Part C	Evaluator 3 Geology Specialist Part A	Part B	Part C
6 Monolithic	1	B	C	C	C	C	C	B	B	C
	2	A	A	A	A	C	C	B	B	B
	3	C	C	B	C	C	C	B	B	A
	4	A	A/A	A	B	B/B	C	B	B/C	B
	5[b]	A	B	A	A	B	C	A	B	B
	Overall Rating		D			D			B	
7 Monolithic	1	B	B	C	A	B	B	B	C	C
	2	B	B	B	B	B	A	C	B	B
	3	A	C	A	B	B	B	A	B	A
	4	A	A/A	B	B	B	B	B	B/C	B
	5[b]	B	B	A	B	B	B	B	B	B
	Overall Rating		B			B			B	
8 Monolithic	1	A	B	C/C	A	A	C	B	C	C
	2	A	B	A/A	A	A	A	C	B	A
	3	A	C	C/A	A	A	B	C	B	B/C
	4	A	A/A	A/B	A	NA/A	B	B	B/C	B/C
	5[b]	A/B	B	A/A	A/B	B	A	A/B	B	B
	Overall Rating		C			B			C	
9 Multiple	1	B	B	C	A	B	A	A	B	B
	2	C	A	A	A	B	A	B	B	B
	3	C	A	C	C	B	A	B	A	A
	4	A	B/B	A	A	NA	B	B	B/C	A
	5[b]	A	B	A	A	B	B	A	B	B
	Overall Rating		D			B			A	
10 Multiple	1	A	C	C	A	B	B	B	B	B
	2	A	B	B	A	B	B	B	B	B
	3	A	C	A	B	B	A	B	B	B
	4	A	B/B	B	A	NA	B	B	B/B	B
	5[b]	B	B	A	B	B	B	B	B	B
	Overall Rating		C			B			B	
11 Multiple	1	B	B	C	C	C	C	A	A	B
	2	B	B	A	C	C	C	B	C	B
	3	C	C	C	C	C	C	C	C	A
	4	A	A/A	A	C	NA/B	C	B	B/B	A
	5[b]	A	B	A	A	B	C	A	B	B
	Overall Rating		C			D			B	
12 Multiple	1	A	B	A	C	C	C	A	A	B
	2	A	B	A	C	C	C	B	C	B
	3	C	C	A/B	C	C	C	C	C	B
	4	A	B/B	A/B	C	NA/B	C	B	B/B	A
	5[b]	B	B	A	B	B	C	B	B	B
	Overall Rating		B			D			A	

[a]See Table XVII

[b]Evaluations on questions A5 and B5 were done by a geochemist

TABLE G-III

EVALUATION RESULTS: SHAFTS

Scheme[a]	Question	Evaluator 1 Heavy Construction Specialist Part A	Part B	Part C	Evaluator 2 Civil Eng. Design Specialist Part A	Part B	Part C	Evaluator 3 Geology Specialist Part A	Part B	Part C
13 Monolithic	1	B	B	C	B	B	B	B	B	B
	2	A	B	A	B	B	B	B	C	B
	3	A	C	C	A	A	B	A	B	A
	4	A	A/A	A	B	B/B	B	B	B/C	A
	5[b]	A	B	A	A	B	B	A	B	B
	Overall Rating		B			B			B	
14 Monolithic	1	A	B	B	B	B	B	B	B	B
	2	A	B	B	B	B	B	A	B	B
	3	A	A	A	B	A	B	A	A	A
	4	A	A/A	B	B	B/A	B	B	B/B	B
	5[b]	B	B	A	B	B	B	B	B	B
	Overall Rating		A			B			B	
15 Multiple	1	A	B	A	A	A	A	A	B	B
	2	A	B	B	A	A	B	B	B	C
	3	A	C	A	B	B	A	B	B	B
	4	A	A/A	A	A	NA/A	B	B	B/B	B
	5[b]	B	B	A	B	B	B	B	B	B
	Overall Rating		A			A			A	
16 Multiple	1	B	B	C	A	A	A	A	A	A
	2	A	B	B	B	B	B	B	B	B
	3	C	C	B	B	B	A	A	B	A
	4	B	B/B	A	B	NA/A	B	A	B/B	A
	5[b]	A	B	A	A	B	B	A	B	B
	Overall Rating		C			B			B	
17 Multiple	1	A	B	C	A	A	B	A	B	B
	2	A	B	B	B	B	A	B	C	B
	3	B	B	C	C	C	B	B	C	B
	4	A	A/A	B	C	NA/A	B	B	B/B	B
	5[b]	A	B	B	A	B	B	A	B	B
	Overall Rating		C			C			C	

[a] See Table XVII

[b] Evaluations on questions A5 and B5 were done by a geochemist

TABLE G-IV

RESULTS OF THE JUDGMENTAL EVALUATION OF THE PROPOSED SCHEMES BY THREE EXPERTS

	SCHEME[a]	OVERALL RATINGS RECEIVED 1	2	3	LOWEST OVERALL RATING RECEIVED	JUDGMENTAL PREFERENCE CATEGORY CATEGORY
Boreholes	1	A	B	A	B	Most Preferred
	2	C	B	A	C	Second Most Preferred
	3	B	B	A	B	Most Preferred
	4	B	D	C	D	Least Preferred
	5	B	A	C	C	Second Most Preferred
Tunnels	6	D	D	B	D	Least Preferred
	7	B	B	B	B[b]	Most Preferred
	8	C	B	C	C	Second Most Preferred
	9	D	B	A	D	Least Preferred
	10	C	B	B	C	Second Most Preferred
	11	C	D	B	D	Least Preferred
	12	B	D	A	D	Least Preferred
Shafts	13	B	B	B	B[b]	Second Most Preferred
	14	A	B	B	B	Second Most Preferred
	15	A	A	A	A[b]	Most Preferred
	16	C	B	B	C	Least Preferred
	17	C	C	C	C[b]	Least Preferred

[a]See Table XVII

[b]Unanimous rating by three evaluators

NOTE:

The following criteria were used in arriving at the "Judgmental Preference Categories" presented in Table G-IV:

- The lowest overall rating received is used to determine the "judgmental preference categories". This will result in conservation in the sense that a scheme (such as 12), which received one poor overall rating, will be ranked low.

- If a scheme's lowest overall rating is "D", it is automatically placed in the "least preferred" category. The rationale for this is that if one of the evaluators has "reservations" about a given scheme, then that scheme has the potential for major problems.

- If a scheme's lowest overall rating is an "A" or a "B" then that scheme is placed in the "most preferred" category. The rationale for this is that a lowest overall rating of "A" or "B" suggests that an evaluator had a "reservation" about the scheme or had given it a "fair" rating. Hence, such schemes have the potential for excellent performance. Furthermore, it was noticed that the evaluators expressed difficulty in choosing between an "A" or "B" rating and some chose "B"s just to be on the safe side.

- If a scheme's lowest overall rating is a "C", then it is placed in the "second" most preferred category. The rationale for this is that at least one evaluator must have identified potential for problems in the given scheme. In addition, most evaluators clearly distinguish between "A" and "B" ratings and a "C" rating.

- In the case of shafts (Table G-III), where not one scheme received a "D" rating and where scheme 15 received a unanimous "A" rating, slightly different criteria are used. Scheme 15 is rated as "most preferred", schemes 16 and 17 as "least preferred". Because all ratings are relative, this should not cause any problems.

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