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Nevada Nuclear Waste Storage Investigations Project

Hydrologic Calculations to Evaluate Backfilling Shafts and Drifts for a Prospective Nuclear Waste Repository in Unsaturated Tuff

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HYDROLOGIC CALCULATIONS TO EVALUATE BACKFILLING SHAFTS AND DRIFTS FOR A PROSPECTIVE NUCLEAR WASTE REPOSITORY IN UNSATURATED TUFF

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ABSTRACT

Preliminary hydrologic calculations were performed to determine if choice of drift backfill could influence water flow past waste packages adjacent to a repository drift in unsaturated volcanic tuff. Additional calculations were performed to determine if water would flow into a shaft that penetrates a nonwelded-welded tuff interface. These hydrologic calculations consisted of numerical simulations using the computer code TRUST. Idealized configurations of a vertical shaft extending to the repository and a repository drift with horizontal and vertical emplacement of waste packages were evaluated. Both fine-grained and coarse-grained materials were considered as backfill to the drift and shaft. In the numerical simulations, coarse-grained backfill material drained more completely than fine-grained material and formed a more effective capillary barrier to water flow. Although the magnitude of flow in the modeled regions is small, selection of backfill was shown to influence flow through the repository drift and vertical shaft. However, it is concluded that selection of backfill does not significantly influence water flow past vertically or horizontally emplaced waste packages.

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PREFACE

The majority of the work described in this report was performed from February 1983 through August 1983 using best available data. Although additional measurements and an improved conceptual understanding of the physical system of Yucca Mountain have been gained since that time, the basic conclusions contributing to development of concepts for sealing a repository in unsaturated tuff remain useful for consideration in the Nevada Nuclear Waste Storage Investigations (NNWSI) project.

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INTRODUCTION TO HYDROLOGIC MODELING FOR SEALING A REPOSITORY IN UNSATURATED TUFF

The Nevada Nuclear Waste Storage Investigations (NNWSI) project, managed by the Nevada Operations Office of the U.S. Department of Energy, has the responsibility for evaluating the feasibility of siting a repository at Yucca Mountain for disposal of high-level nuclear waste. Yucca Mountain is located on and adjacent to the Nevada Test Site (NTS) in an extremely dry region of the United States, between the Mojave and Great Basin deserts (Fig. 1). Key considerations for siting a nuclear waste repository at Yucca Mountain are the partially saturated (unsaturated) condition of the host rock and the quantity of water movement that is typically limited through thick unsaturated zones of the desert environment (Winograd 1981). Yucca Mountain consists of layered air fall and ash flow volcanic tuffs dipping from 4 to 8 degrees to the east (Fig. 2). The volcanic tuffs range from densely welded to nonwelded; where welded, the tuffs are likely to be fractured (Winograd and Thordarson 1975). Thickness of the unsaturated zone within the boundary of the prospective repository at Yucca Mountain varies from 500 to 750 m (DOE 1984).

As part of the evaluation of Yucca Mountain for suitability as a nuclear waste repository, the Sandia National Laboratories (SNL) Geotechnical Projects Division 6313 has the responsibility to investigate methods and materials for sealing the potential repository and entrance shafts and to develop appropriate sealing designs. One of the first tasks of the NNWSI repository sealing program is to develop concepts for design of sealing components. To assist in establishing these concepts, hydrologic calculations were performed by the Pacific Northwest Laboratory (PNL). Parallel hydrologic calculations were also made at SNL (Mondy and Baker 1983), but only results from PNL are presented in this report.

The calculations investigate water flow in the vicinity of waste packages near repository drifts and water flow in and around shafts extending to the repository facility. As used in this report, waste packages consist of the waste form and any other containers and materials placed around the waste and a drift is a horizontal, or nearly horizontal, mined passageway in the

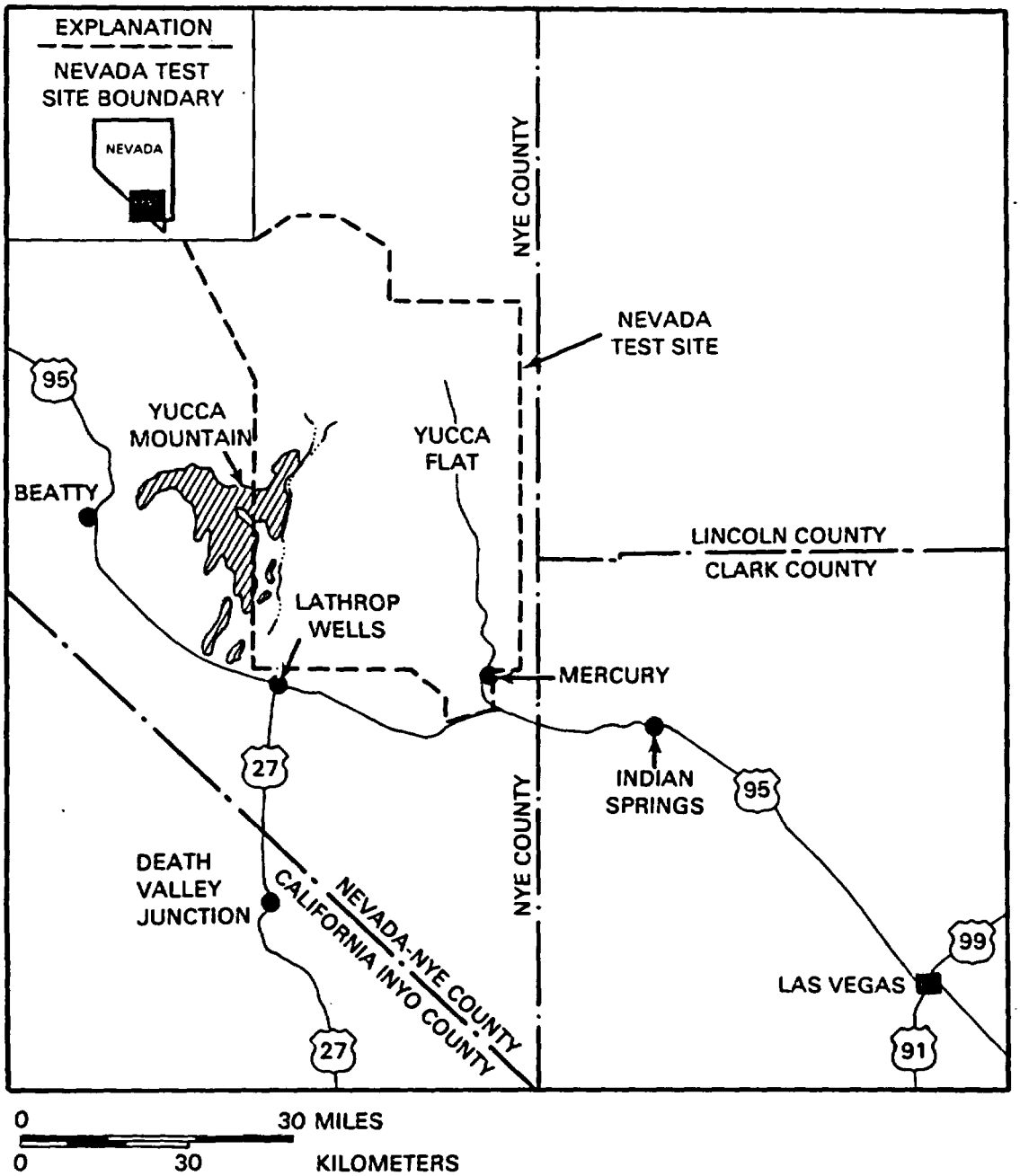
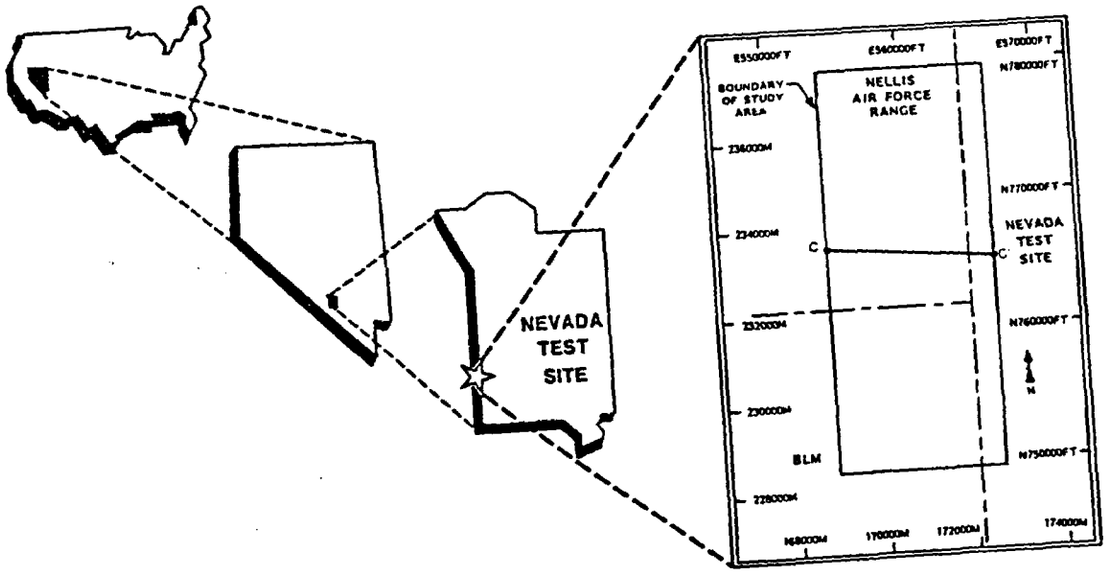


FIGURE 1. Location Map for the Nevada Test Site and Yucca Mountain (After Winograd and Thordarson 1975)



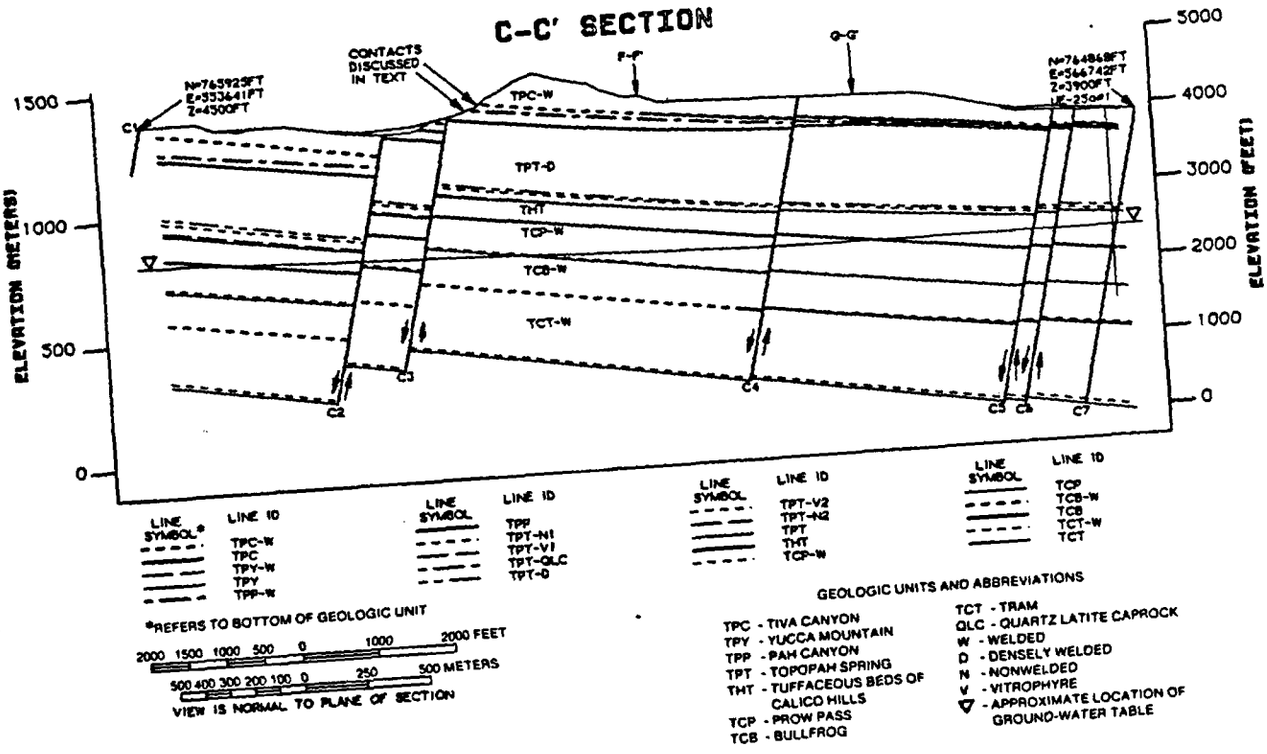


FIGURE 2. East-West Geologic Cross Section Through Yucca Mountain (Nimick and Williams 1984)

repository. A shaft is a vertical or near-vertical excavation of limited area when compared with its depth for the purpose of opening and servicing an underground working such as a mine or repository. Three idealized configurations were evaluated by numerical simulation: 1) a repository drift with horizontal emplacement of waste packages, 2) a repository drift with vertical emplacement of waste packages, and 3) a shaft intersecting a contact between welded and nonwelded stratigraphic units.

The preliminary calculations focused on determining the type of materials that may be useful as backfill. Coarse-grained materials may be a moderately to lightly crushed tuff; fine-grained backfill may consist of a highly crushed tuff. Material characteristics used in the calculations were those of sand and clay, selected to hydrologically represent a possible range of backfill.

Appendices A and B describe the code used, the approach to modeling, and the input used for the preliminary hydrologic calculations. Appendices C through E describe each idealized configuration modeled and discuss results of the calculations.

SEALING A REPOSITORY IN THE UNIQUE ENVIRONMENT OF UNSATURATED TUFF

The overall system performance objective for a prospective geologic repository following permanent closure as specified by the U.S. Nuclear Regulatory Commission (NRC) is from NRC (1983) Section 60.112:

> "The geologic setting shall be selected and the engineered barrier system and the shafts, boreholes and their seals shall be designed to assure that releases of radioactive materials to the accessible environment following permanent closure conform to such generally applicable environmental standards for radioactivity as may have been established by the Environmental Protection Agency with respect to both anticipated processes and events and unanticipated processes and events."

While concern has been expressed over the possible rate of escape to the atmosphere of gaseous radionuclides (Roseboom 1983 and NRC 1984), only the characteristics of fluid flow in unsaturated materials are considered in this report.

The key to achieving the performance objectives outlined in Section 60.112 are the engineered barrier system and the geologic setting for the repository. The NRC has specified provisions for the design of seals for shafts and boreholes associated with the long-term performance of a geologic repository as follows (NRC 1983):

60.134 Design of seals for shafts and boreholes

(a) General design criterion. Seals for shafts and boreholes shall be designed so that following permanent closure they do not become pathways that compromise the geologic repository's ability to meet the performance objectives for the period following permanent closure.

(b) Selection of materials and placement methods. Materials and placement methods for seals shall be selected to reduce, to the

extent practicable: 1) the potential for creating a preferential pathway for groundwater; or (2) radioactive waste migration through existing pathways.

As suggested by the provisions in Section 60.134 and Ostrowski et al. (1984), engineered barriers for a prospective repository should be designed, where possible and reasonable, to assist the geologic setting in meeting the specified performance objectives. One possible way that the engineered barrier could contribute to the performance of the waste package would be for the drift backfill to influence water flow in the vicinity of the waste package. Reducing water flow would result in a drier environment and possibly result in a lower release of radionuclides. Consequently, the analyses described in this report were designed to assess the influence of various backfill materials on the flow and moisture retention in the vicinity of waste packages.

The arid conditions of Yucca Mountain are especially suited for disposal of high-level nuclear waste because the lack of available water enhances the limited potential for contact between percolating water and waste (Klingsberg and Duguid 1980; Roseboom 1983). If the nuclear waste were placed in the welded tuff of the Topopah Spring Member of the Paintbrush tuff, as suggested in reports on repository horizon selection (Johnstone et al. 1983) then a vitric bedded tuff sequence will be above the host rock, and the nonwelded tuffaceous beds of the Calico Hills will be below the host rock. This vitric bedded tuff sequence (generally porous rock with few open fractures) theoretically forms a barrier that dampens any surges of percolation from precipitation events (Roseboom 1983).

In establishing rationale for the types of materials to be considered in the analyses, results from other researchers investigating performance of capillary barriers in shallow subsurface disposal of low-level radioactive waste were evaluated. Corey and Horton (1969) considered burial of solid waste using gravel lenses to protect the waste from leaching by percolating rain water. The solid waste included obsolete process equipment, spent ion-exchange resins, reactor fuel tube housings, and fragments of experimental elements. Frind et al. (1976) analyzed the feasibility of using gravel and fine-grained

soil layers to isolate large quantities of medium- or low-activity radioactive waste in the shallow subsurface. More recently, Johnson et al. (1983) investigated the use of layered soil covers with contrasting texture for trenches containing low-level radioactive waste. In each of these studies, capillary barriers were shown to substantially reduce infiltration through the waste-storage facilities. The analyses described in this report extend the concept of capillary barriers to possible deep disposal of high-level radioactive waste in the unsaturated zone of Yucca Mountain.

MODEL APPROXIMATIONS TO THE PHYSICAL SYSTEM

As with any modeling exercise, the model used for the preliminary calculations is, at best, an approximation to the physical system being represented. This is particularly the case for models of natural ground-water systems. A number of assumptions were made for simulating water flow in the vicinity of the potential repository in Yucca Mountain with the computer code TRUST. The assumptions for modeling are listed below, and a discussion of each follows:

- Water flow was assumed to occur in the rock matrix for the hydrologic calculations.
- Steady-state was assumed to have been reached when the difference in flux into and out of the system was less than 5 percent.
- The steady-state influx to the modeled region in the form of recharge was assumed to be 0.4 cm/yr.
- The predominant hydraulic gradient driving the flow system was vertical and produced downward flow of water.
- Fluid flow was assumed to occur only in the liquid phase. Vapor transport of water was not considered.
- Isothermal conditions were assumed to exist; fluid properties did not change in either space or time.
- Hysteresis of moisture retention characteristics and unsaturated permeability for materials simulated was not considered.
- The rock matrix was assumed to be incompressible.

The basic philosophy for modeling was to assume that water flows through the matrix in the fractured tuff of Yucca Mountain. The water flux through the rock media was assumed to be less than the saturated hydraulic conductivity of the rock matrix. Hence, it is reasonable to assume that the fractures do not

transmit water and they were not included in the analyses. Hydrologic properties of the tuff matrix used in the analyses are reported in Gee (1982)[a].

The densely welded portion of the Topopah Spring Member of the Paintbrush Tuff was selected (Johnstone et al. 1984) as the most suitable geologic unit in which to construct a nuclear-waste repository in Yucca Mountain. Available data indicate that porous flow through the tuff matrix, rather than fracture flow, dominates under the prevailing flux conditions in Yucca Mountain (DOE 1984). However, as our understanding of flow through unsaturated fractured rock increases, it may be useful to consider the influence of fractures on water flow through Yucca Mountain. If modeling flow through unsaturated fractured rock is needed to characterize flow through Yucca Mountain, additional laboratory and field testing may be required. In addition, because analyzing water flow in unsaturated fractured rock has only recently begun to receive attention (Evans 1983) and the tools to perform such analyses are not well developed, it will be necessary to develop the proper analytical tools for modeling water flow through unsaturated fractured rock.

Steady state was assumed to have been reached when the difference in flux into and out of the system was less than 5 percent. The steady-state approach was assumed because of the low rate of recharge and probable attenuation of moisture pulses at depth in the unsaturated zone at Yucca Mountain. Changes to the transient flow system may occur within the time frame of pluvial events. The most recent pluvial event or water table rise in southern Nevada was during the Late Pleistocene (Winograd 1981), which is an estimated 185,000 to 25,000 years before present (Andrews 1975, p. 64) indicating that the steady-state assumption is reasonable.

The steady-state infiltration rate of 0.4 cm/yr was obtained from assuming that 2 percent of 20 cm average annual precipitation becomes recharge at Yucca Mountain (Fernandez and Freshley 1983). Assuming constant influx to the models was reasonable for the steady-state solutions considered because the annual

(a) Gee, G. W. 1982. Laboratory Report on the Unsaturated Flow Characteristics of Core Samples from Nevada Test Site Well USW GU-3, Interim Status Report to SNL from PNL, October, 65 p.

cyclic variation of recharge is likely attenuated at the potential repository horizon by the overlying unsaturated porous rock (Roseboom 1983).

Current data suggest that the recharge may be less than 0.4 cm/yr (DOE 1984). However, because we are using the modeling results in a comparative sense, we anticipate that changing the upper boundary condition will not significantly alter our conclusions.

A vertical hydraulic gradient was assumed at the prospective repository depth. Typically, in the thick unsaturated zones of arid regions, water flow is predominantly downward below shallow root systems and the near surface where evaporation can occur (Winograd 1981).

Assuming that fluid flow occurs only in the liquid phase makes the repository sealing calculations conservative in that more water is available. Evans (1983) states that water in unsaturated host rock will evaporate because of elevated temperatures near the repository as a result of radioactive waste decay. Induced thermal gradients may then cause vapor-phase flow away from the waste and recondensation in cooler rocks farther from the repository. Considering liquid flow alone allows the model to predict more water flow to occur into the repository horizon than if we considered flow of both liquid and vapor.

Following perturbation from construction and closure of the repository, a period of time will be required for the flow system to reach steady state. It was assumed that this postclosure period will be sufficiently long for temperatures near the repository to approach a constant value.

Hysteresis of the hydraulic characteristics for host-rock formations and backfill materials was not considered because, at steady state, this phenomenon was assumed to be unimportant. In addition, data on hysteresis of moisture retention characteristics were not available for the samples of tuff from Yucca Mountain.

An incompressible matrix was assumed for simulating the volcanic tuff units and backfill materials. Compressibility of geologic materials under unsaturated conditions is a complicated process (Narasimhan and Witherspoon 1977), and these data have not been collected. Further, because the effects of

media compressibility are important only near saturated conditions and because the tuff remained partially saturated in the analyses, the incompressible matrix assumption was considered reasonable.

SUMMARY OF THE HYDROLOGIC CALCULATIONS

Investigators at PNL performed preliminary hydrologic calculations to consider backfilling portions of a prospective nuclear waste repository in the volcanic tuff of Yucca Mountain. Materials representing both highly and lightly crushed tuff were considered as backfill. The calculations were completed using the computer code TRUST. Description of flow in unsaturated media and the TRUST code are included in Appendix A. Appendix B contains a description of the modeling approach and Appendices C and D, respectively, describe results from analysis of the repository drift and vertical shaft.

Three model configurations for the repository drift and entrance shaft were considered for the sealing calculations. The first two configurations were a drift with horizontal emplacement of waste packages (Fig. C.1) and vertical emplacement of waste packages (Fig. C.2). The third configuration was a vertical entrance shaft to the repository intersecting a stratigraphic contact between tuff formations (Fig. D.1).

Hydraulic characteristics for volcanic tuffs in Yucca Mountain were obtained from Gee (1982). The moisture retention characteristics and unsaturated permeabilities for the tuffs are described in Appendix B. The characteristics of both welded and nonwelded tuff were used in the calculations. Tuff samples were selected on the basis of their hydrogeologic properties, rather than being correlated with stratigraphy of the borehole they were taken from. This substitution was assumed to be reasonable because lateral variation of volcanic tuff is commonly observed at the NTS (Winograd and Thordarson 1975), and uncertainties exist as to the representative nature of individual samples. The hydraulic characteristics of backfill simulated as sand and clay were obtained from Mualem (1976a).

Following selection of hydraulic characteristics for materials, a numerical test was conducted to determine the grid spacing appropriate for the calculations presented in this report. The grid spacing analysis is described in Appendix B.

Preliminary results from simulating water flow near horizontal emplacement of waste packages indicated that the two-dimensional analysis illustrated in Figure C.1 was inadequate, and a three-dimensional analysis would be required if detailed characterization of the flow system is needed. Rather than developing a large three-dimensional model, we determined that useful conclusions could be extrapolated from analysis of vertical emplacement of the waste packages, which can be modeled in two dimensions (Fig. C.2).

Analysis of the repository drift with vertical emplacement of waste packages demonstrated that sand, used to simulate coarse-grained backfill, drained more completely than clay, which was used to simulate fine-grained backfill (see Appendix C). The drained sand backfill formed a capillary barrier to water flow and distorted pathlines farther away from the drift and waste package than the drift with clay backfill. Also, permeabilities inside the drift were significantly lower for the case with sand backfill.

The analysis of the vertical repository shaft (see Appendix D) provided results similar to the repository drift analysis in terms of the behavior of backfill materials. The sand backfill drained more completely than clay. However, the investigation of the repository shaft demonstrated that transient perched water can occur at material interfaces as a transient condition. This occurred primarily because of the initial conditions selected and the model used. The transient occurrence of perched water in the simulations also suggests that the steady-state approach may not be adequate for modeling all aspects of sealing a prospective repository in unsaturated volcanic tuff.

CONCLUSIONS FROM THE HYDROLOGIC CALCULATIONS

The hydrologic calculations considered the effectiveness of backfill materials as barriers to water flow in simple repository configurations. Based on results of the preliminary calculations, the following conclusions are made concerning sealing the prospective nuclear waste repository in tuff:

- From a hydrologic perspective, by approximating an open drift with coarse sand in numerical simulations, backfilling the drifts and shafts does not appear to be essential because backfill material cannot significantly influence flow past waste packages (see Tables C.1 and C.3 in Appendix C and Table D.2 in Appendix D). However, backfill may be desired for structural or other reasons (Roseboom 1983).

- If backfilling the repository is required, results of numerical simulations (see Table C.3 in Appendix C and Table D.2 in Appendix D) indicate that coarse materials perform more satisfactorily as barriers to water flow through drifts and shafts than fine materials in the unsaturated zone. This conclusion is supported by the research on capillary barriers by Corey and Horton (1969), Frind et al. (1976), and Johnson et al. (1983).

- Regardless of the backfill material modeled, more water flows into the repository drift when the surrounding host-rock formation is at high saturation (i.e., 98-99 percent; see Table C.3 in Appendix C). When the surrounding host-rock formation is at high saturation, approximately 17 percent of influx to the modeled region entered the drift as compared to less than 0.6 percent for the remainder of the cases analyzed. For these cases, the surrounding host-rock formation was at approximately 90 percent saturation.

- The influence of drift backfill material on flow past waste packages appears to be greater for vertical emplacement of packages than for horizontal emplacement of the packages. As illustrated by pathlines in Figures C.9, C.10, C.13 and C.14 (Appendix C), the influence on

water flow of backfill in the drift is limited in the horizontal direction. This is due to the predominantly vertical hydraulic gradient in the modeled regions.

APPENDIX A

DESCRIPTION OF UNSATURATED FLOW AND THE COMPUTER CODE TRUST

APPENDIX A

DESCRIPTION OF UNSATURATED FLOW AND THE COMPUTER CODE TRUST

The energy state of water in unsaturated geologic media is generally described in terms of potential energy. Water in geologic media moves in response to differences in potential energy, always in the direction of a lower energy state. Hydraulic head (H) with dimensions of length [L] represents water potential as energy per unit weight and is the sum of pressure head ϕ [L] and elevation head z [L] such that

$$H = \phi + z \tag{A.1}$$

where z is elevation above a datum. In the unsaturated zone, pressure head is negative because work is required to extract water against rock-matrix forces.

A complete description of the state of water in unsaturated media requires definition of the volumetric moisture content. Volumetric moisture content, or simply moisture content, is the ratio of water-filled voids to total volume. Saturation expresses the ratio of water-filled voids to total void space, or porosity. The magnitude of pressure head determines the moisture content and saturation. Pressure head is related to moisture content through the moisture retention characteristics.

The equations for flow in the unsaturated zone may be solved analytically or numerically (Lappala 1982). However, analytic solutions are generally limited to field problems with simple geometries, and numerical solution techniques must be used for complex problems.

DESCRIPTION OF TRUST

TRUST is a multidimensional, integrated finite difference (IFD) computer code for simulating variably saturated water flow in deformable media (Reisenauer et al. 1982). TRUST is a modification of TRUMP, a code for determining transient and steady-state distributions of temperature in solids. The

similarity between conductive heat transfer and fluid flow in porous media enables the calculational framework for TRUMP to be transferred to TRUST.

In TRUST, the unsaturated flow system is described by the following generalization of Richards' equation (Narasimhan et al. 1978):

$$\nabla \cdot [K(\phi) \nabla (z + \phi) = M_c(D\phi/Dt) \qquad (A.2)$$

where ϕ = pressure head

$K(\phi)$ = unsaturated hydraulic conductivity [L/t] as a function of pressure head

z = elevation head

M_c = the fluid mass capacity

D/Dt = the material derivative.

The fluid mass capacity consists of terms describing compressibility of the fluid, compressibility of the matrix, and changes in moisture content caused by changes in pressure head.

An integral representation of Richards' equation is used in TRUST, where physical properties of the system are averaged over representative subdomains or elements. Spatial gradients are approximated by finite differences and a mixed explicit-implicit iterative scheme is used to advance in the time domain. The derivation of mathematical equations and a description of the numerical representation of them in TRUST is available in the sequence of papers by Narasimhan and Witherspoon (1977), Narasimhan et al. (1978), and Narasimhan and Witherspoon (1978).

The activities for using TRUST include the following: defining the hydraulic properties of materials, specifying properties of the fluid, defining the initial and boundary conditions, and defining a grid. For steady-state flow problems, only the boundary conditions are required; initial conditions represent an initial guess for iterating through the transient case to steady state.

HYDRAULIC PROPERTIES OF MATERIALS REQUIRED FOR TRUST

The mathematical statement of unsaturated flow (Equation A.2) requires definition of the moisture retention characteristic and unsaturated hydraulic conductivity or permeability for each material. The moisture retention characteristics of a geologic medium can be easily determined in the laboratory. At zero pressure head, the medium is most often fully saturated. Decreasing the pressure head causes progressively smaller void spaces to empty, defining the moisture retention characteristics.

While saturated hydraulic conductivity is relatively easy to measure, unsaturated hydraulic conductivity is more difficult to determine. In addition, natural variation of geologic materials makes numerous replications necessary to obtain representative hydraulic conductivities. Because of these difficulties, considerable effort has been made to develop analytical models to calculate unsaturated hydraulic conductivity and avoid direct measurement.

Most models for calculating unsaturated hydraulic conductivity or permeability are derived from the shape of measured moisture retention characteristics. The theory of these models is based on the assumption that the medium has interconnected pores of radius r that can be represented by capillary tubes.

The model of Mualem (1976b) was used for this study. Mualem's algorithm for relative unsaturated hydraulic conductivity ($K_r(S_e) = K(\theta)/K_{sat}$) is

$$K_r(S_e) = S_e^{1/2}\left[\int_0^{S_e} dS_e \;\; \psi \int_0^1 dS_e/\psi\right]^2 \qquad (A.3)$$

where the effective saturation S_e is given by

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} \qquad (A.4)$$

θ_s is the saturated moisture content and θ_r represents residual moisture content. The residual moisture content reflects the smallest pore size involved with liquid capillary flow. A computer program described by McKeon et al. (1983) was used to evaluate the integrals of equation (A.3) and calculate $K_r(S_e)$.

TRUST requires permeability as a function of pressure head. Permeability k [L^2] is a property of the medium alone and is related to hydraulic conductivity K [L/t] through properties of the fluid by the equation

$$K = \frac{k \rho g}{\mu} \tag{A.5}$$

where ρ is the density of water [M/L^3], g is acceleration of gravity [L/t^2], and μ is the dynamic viscosity of water [M/Lt].

BOUNDARY CONDITIONS

The boundary conditions for TRUST can be specified as no flow, prescribed head, or prescribed flux. Typically for problems of unsaturated flow, the upper horizontal boundary is one of recharge, or infiltration, which is represented by prescribed flux. The lower boundary may be the water table, which is modeled as prescribed head. Lower boundaries may also be represented by a gradient condition. If planes of symmetry are used, the vertical boundaries will be no flow boundaries; however, prescribed head and prescribed flux conditions are possible.

APPENDIX B

DESCRIPTION OF THE MODELING APPROACH

APPENDIX B

DESCRIPTION OF THE MODELING APPROACH

This appendix describes sources of data and preparation for input to the models investigating repository sealing. The material and fluid properties, grid spacing, and upper and lower boundary conditions are discussed.

HYDRAULIC PROPERTIES OF MATERIALS

The unsaturated hydraulic characteristics were specified for both the volcanic tuff units and backfill materials. The continuum representation was assumed for the fractured, welded tuffs, and measured properties of the matrix were used. In addition, because data on the hydraulic characteristics of backfill were not available, substitutions from the literature were made.

Hydraulic characteristics for materials used to represent the volcanic tuff units are from Gee (1982).[a] Gee (1982) measured moisture retention characteristics and saturated hydraulic conductivity of 19 core samples from well USW GU-3 on Yucca Mountain. The moisture retention characteristics were measured with a pressure plate extractor in the wet range of the samples and with a vapor equilibrium procedure in the dry range. Saturated hydraulic conductivities were measured using a falling-head or constant-head permeameter. The saturated conductivities were then converted to permeabilities for input to the models.

The samples from USW GU-3 reported in Gee (1982) were retested and the data combined with that from an additional 29 core samples into Peters et al. (1984). The additional core samples were from well USW G-4. Data from the samples included measurements of matrix and fracture hydraulic properties. The report by Peters et al. (1984) has been published in support of the NNWSI Environmental Assessment (DOE 1984).

(a) Gee, G. W. 1982. Laboratory Report on the Unsaturated Flow Characteristics of Core Samples from Nevada Test Site Well USW GU-3, Interim Status Report to SNL from PNL, October, 65 p.

The saturated hydraulic characteristics of tuff samples from Gee (1982) used for the repository sealing analyses are listed in Table B.1. Tuff sample S-19 was selected to represent the welded-tuff host rock for analysis of the repository drift. Gee (1982) reported that sample S-19 is moderately welded with porosity and saturated permeability that are greater than most of the other welded tuff samples. The higher porosity and permeability of the moderately welded tuff were expected to cause fewer numerical difficulties in the calculations than the densely welded tuff. Additionally, sample S-19, with an input flux of 0.4 cm/yr, resulted in saturation of the host-rock formation

TABLE B.1. Porosity and Saturated Permeability of Materials Used for the Repository Sealing Analyses

Material	Source[a]	Porosity	Saturated Permeability (m^2)
S-19 (W)[b]	G	0.22	1.21×10^{-16}
S-19 (W) (k_s increased)	G	0.22	1.21×10^{-14}
S-19 (W) (k_s decreased)	G	0.22	1.80×10^{-17}
S-17 (N)	G	0.35	7.10×10^{-16}
S-14 (N) (k_s decreased)	G	0.27	1.35×10^{-17}
S-4 (W)	G	0.05	4.92×10^{-16}
S-4 (W) (k_s increased)	G	0.20	8.54×10^{-15}
Chino clay	M	0.53	3.92×10^{-16}
Chino clay (k_s decreased)	M	0.53	1.40×10^{-17}
Crab Creek sand	M	0.37	1.93×10^{-13}

(a) G denotes Gee et al. (1982); M denotes Mualem (1976a).
(b) W denotes welded tuff; N denotes nonwelded tuff.

of 89 percent, which is within the range reported for the prospective repository horizon (as summarized in Fernandez and Freshley 1983). Figures B.1 and B.2 illustrate the moisture retention characteristics and unsaturated permeability relationships for sample S-19 from Gee (1982). The additional curves in Figure B.2 represent cases where the saturated permeability of sample S-19 was increased and decreased for simulation of vertical emplacement of waste canisters.

Samples S-4, S-14, and S-17 from Gee (1982) were used in the analysis of the vertical repository shaft. These samples were selected to investigate the

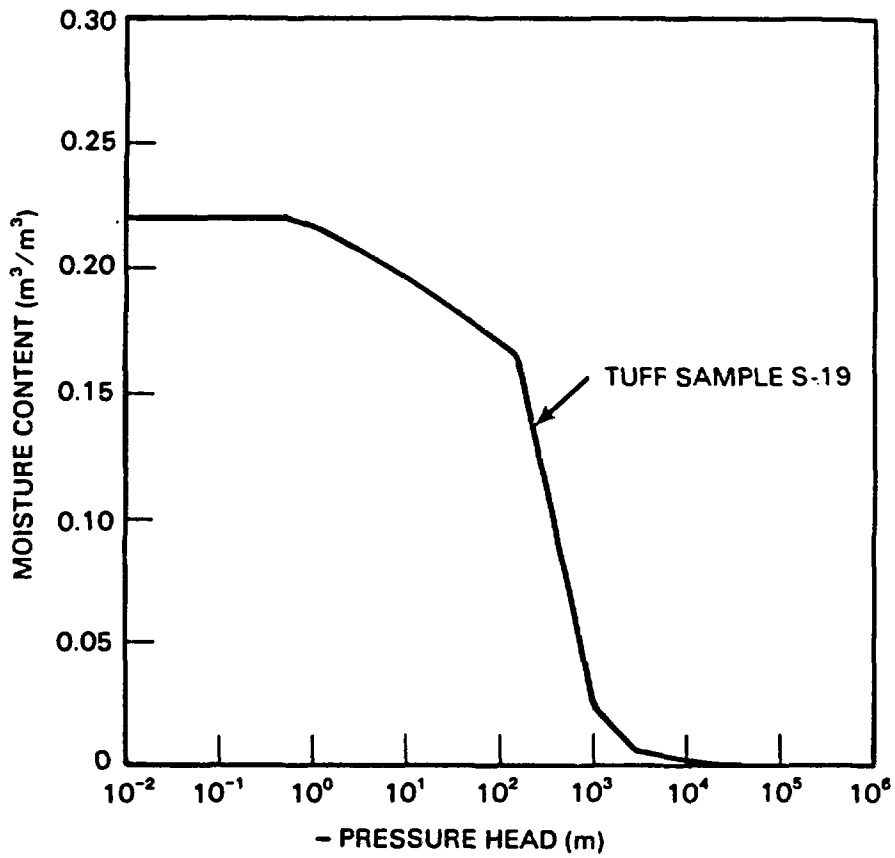


FIGURE B.1. Moisture Retention Characteristics of the Host-Rock Formation for Analysis of the Repository Drift (Source: Gee 1982.)

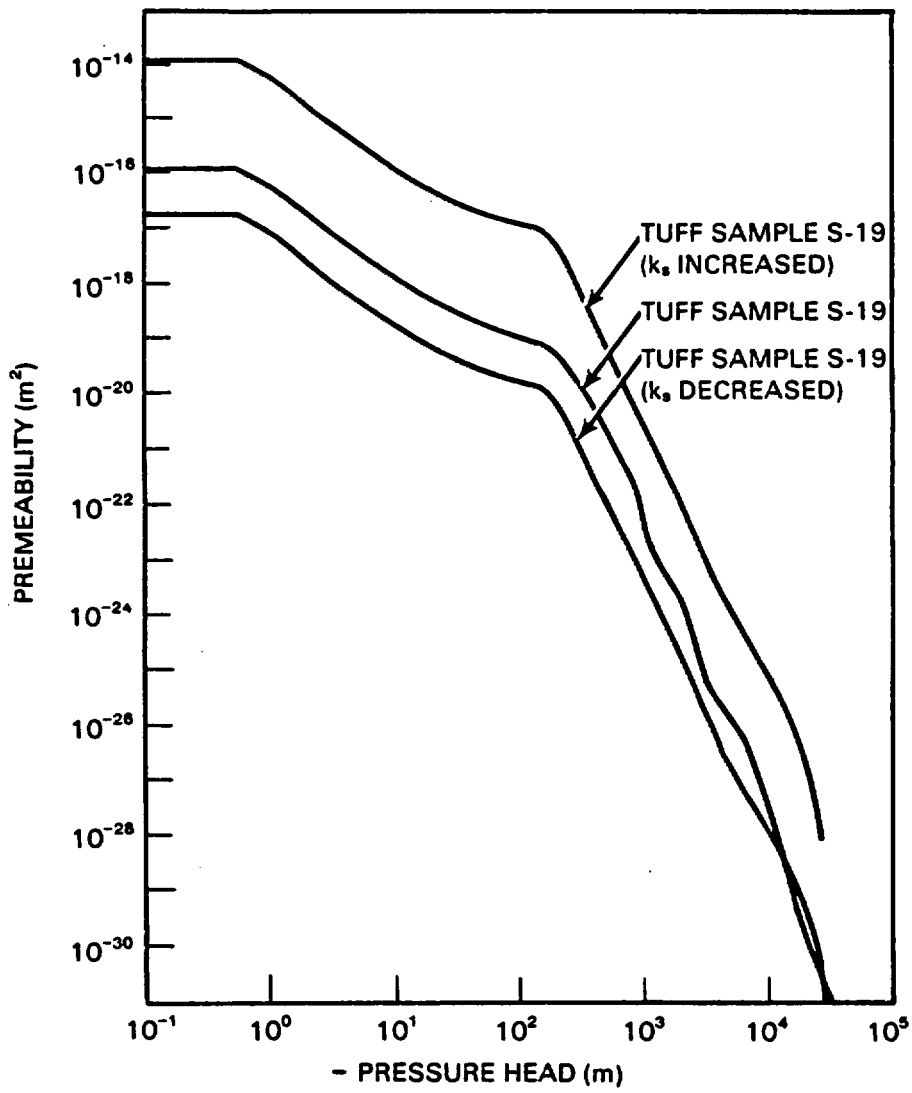


FIGURE B.2. Unsaturated Permeability of Host-Rock Formations for Analysis of the Repository Drift (Source: Gee 1982.)

effects of contrasting porosity and permeability of volcanic tuff units intersected by a vertical repository shaft. The saturated permeabilities were increased and decreased for samples S-4 and S-14, respectively. Figures B.3 and B.4 illustrate the hydraulic characteristics for materials used to simulate the host tuff units in the analysis of the vertical repository shaft.

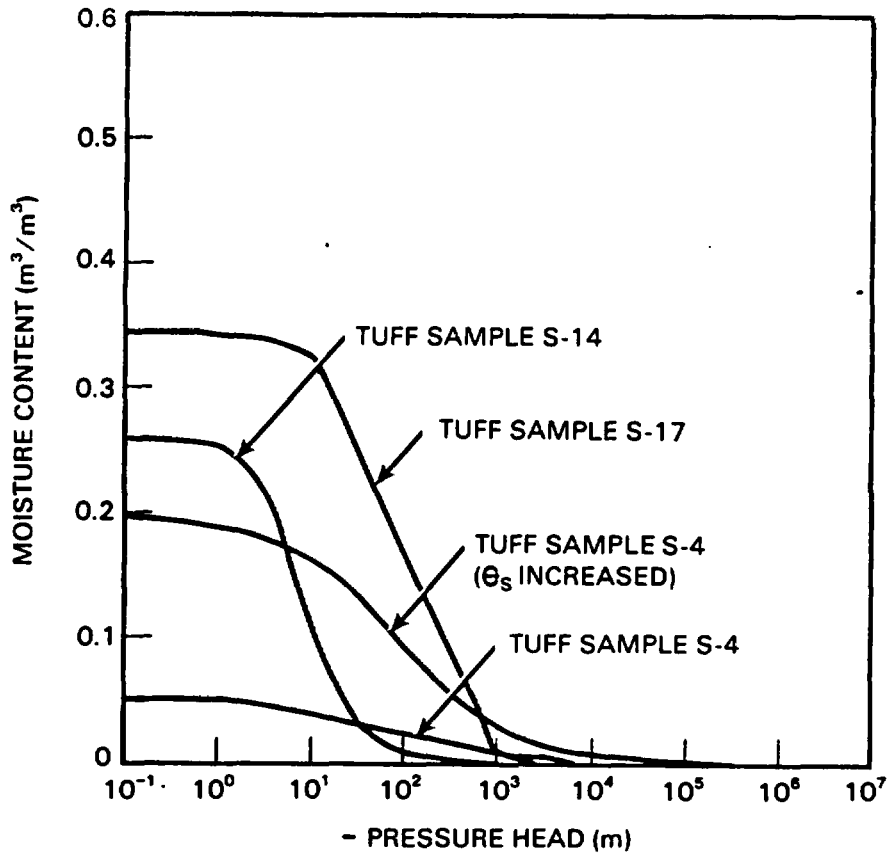


FIGURE B.3. Moisture Retention Characteristics of Volcanic Tuff Samples for Analysis of the Vertical Repository Shaft (Source: Gee 1982.)

Both clay and coarse-grained sand were substituted as backfill to bound the effects of coarse-grained and fine-grained material in the configurations simulated because no sample backfill material was available. Hydraulic properties for the Chino clay and Crab Creek sand were selected from A Catalogue of the Hydraulic Properties of Unsaturated Soils by Mualem (1976a). Figures B.5 and B.6 illustrate the moisture retention characteristics and unsaturated permeability of the sand and clay.

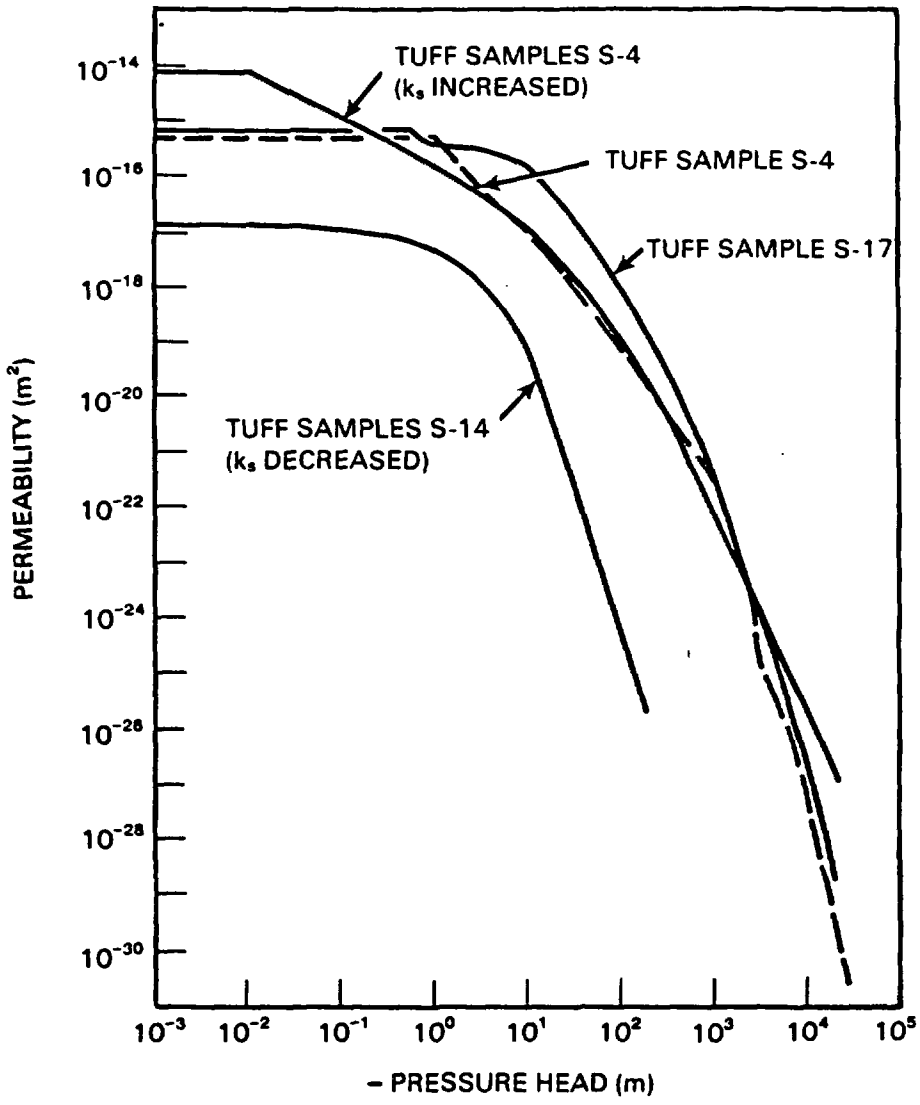


FIGURE B.4. Unsaturated Permeability of Volcanic Tuff Samples for Analysis of the Vertical Repository Shaft (Source: Gee 1982.)

The clay and sand were selected to represent a range of possible backfill materials. The Chino clay was selected to represent the limiting case for fine-grained backfill. The Crab Creek sand was used to simulate coarse-grained backfill that drains rapidly. Note that the clay retains water at decreasing pressure head while, for sand, both moisture content and permeability decrease rapidly with decreasing pressure head.

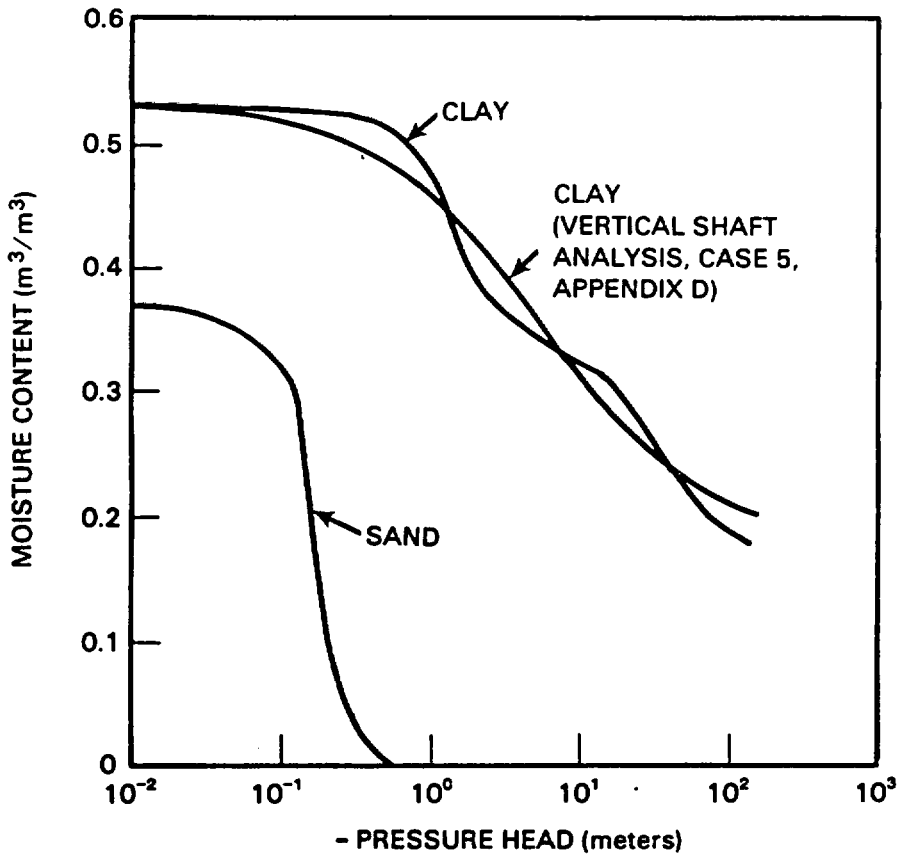


FIGURE B.5. Moisture Retention Characteristics of Materials Simulated as Backfill (Source: Mualem 1976a)

The moisture retention characteristic of clay for the vertical shaft analysis in Figure B.5 has a different shape than the original moisture characteristic for clay. The moisture characteristics for clay and samples S-14 and S-4 (see Fig. B.3), with total porosity increased for the vertical shaft analysis, were least squares fit with with a functional relationship developed by Haverkamp and described by McKeon et al. (1983). The unsaturated permeability relationships for samples S-4 and S-14 in Figure B.4 and clay (for the vertical shaft analysis) in Figure B.6 were derived from the functional fit of moisture retention characteristics. The computer code for fitting moisture characteristics with Haverkamp's functional relationship was not available for most of the repository sealing investigations so it was not used for all samples. However,

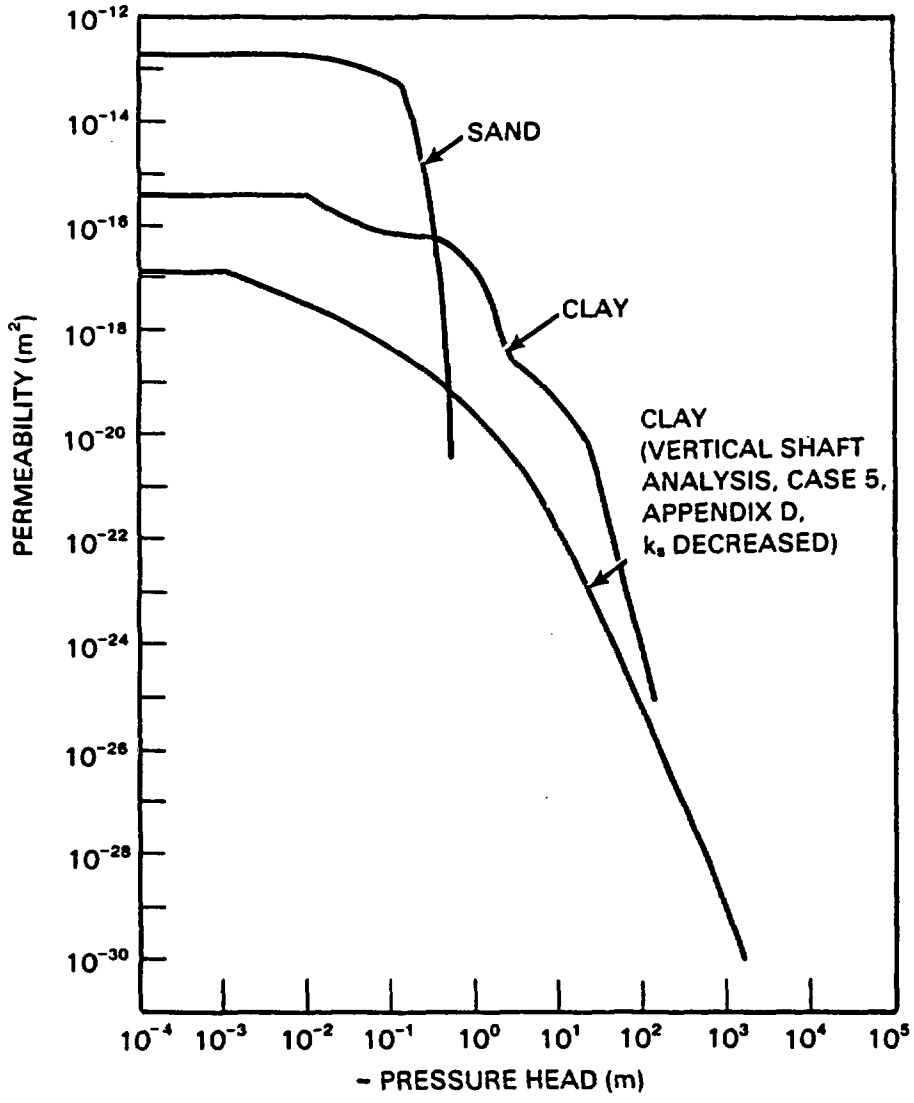


FIGURE B.6. Unsaturated Permeability of Materials Simulated as Backfill (Source: Mualem 1976a)

as illustrated for the clay in Figure B.5, the statistical least squares fit of Haverkamp's functional relationship used in Case 5 (see Appendix D) of the vertical shaft analysis will tend to average variation of the data.

PROPERTIES OF THE FLUID

The properties of water vary with temperature. Fluid properties for the simulations were referenced to 32°C, and conditions near the repository were assumed to be isothermal. At 32°C, the viscosity of water is 60.9 kg/m•day, and the density is 993.72 kg/m^3. The assumed temperature for the repository sealing investigations was based on the position of the potential repository and the geothermal gradient measured in well USW-G4 at Yucca Mountain (Fernandez 1983).[a]

DETERMINATION OF PROPER GRID SPACING

Often the physical parameters of a flow system define the grid spacing appropriate for analysis. In many studies, this important dependence is ignored or approached from the standpoint of previous experience. The importance of grid spacing for modeling flow in Yucca Mountain was demonstrated in a previous investigation (Freshley and Dove 1983). A simple analysis for determining proper grid spacing that eliminated much of the subjectivity is presented in this section.

After considering the anticipated dimensions of the prospective repository facility and entrance shafts, the analysis of grid spacing was performed on a 12-m by 12-m square. The material used in the analysis was tuff sample S-19, from Gee (1982). Boundary conditions were the same as for the hydrologic calculations; the upper boundary was prescribed flux, the lower boundary was prescribed head.

The square region was modeled using progressively finer integrated finite difference (IFD) cells with side dimensions of 4, 3, 2, and 1 m. Sizes of cells tested reflected an expected range for modeling. Illustration of the grid for 4-m cells is included as an example (Fig. B.7); grids with 3-, 2-, and 1-m cells have totals of 16, 36, and 144 cells, respectively.

Three parameters were considered as measures of proper grid spacing: average pressure head over the square, iterations required for solution, and

(a) Fernandez, J. A. 1983. Written communication from SNL to PNL, Richland, Washington, March 2.

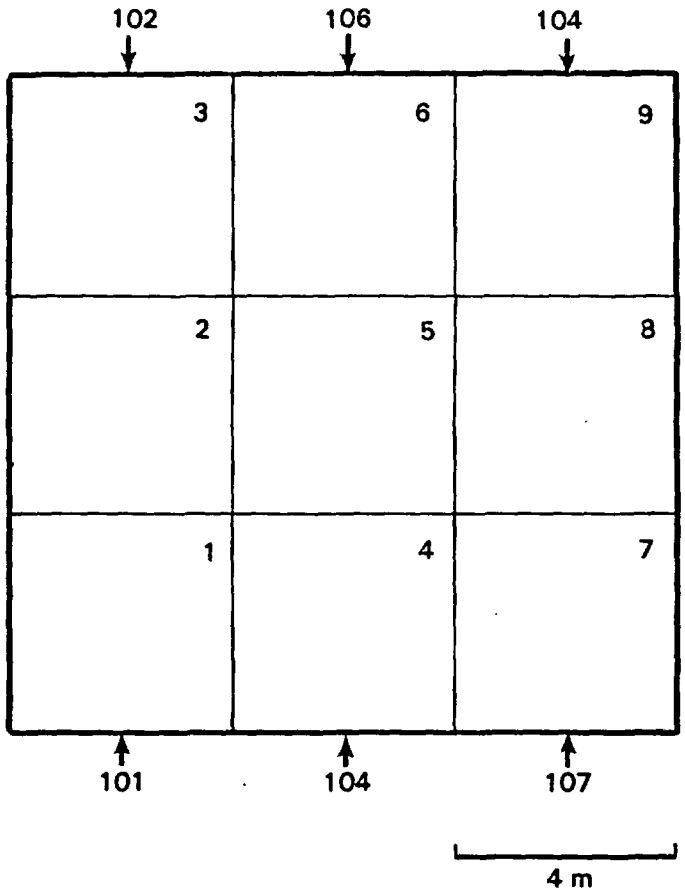


FIGURE B.7. IFD Mesh for the Cells With Side Dimension of 4 m for Investigation of Proper Grid Spacing

time of computation. The objective criteria for proper grid spacing depended on the parameter being analyzed. In Figures B.8 and B.9, the rate of change of computational time and average pressure head served as a criterion for grid spacing. Figure B.10 demonstrates use of a minimum value as the criteria in analysis of the number of iterations.

Each parameter considered for analysis of grid spacing described a different property of the flow system. Average pressure head over the square reflected convergence of the numerical solution. The criterion for proper cell size using pressure head was that the solution did not change with an increasingly finer mesh. Computational time corresponded directly with cost of the

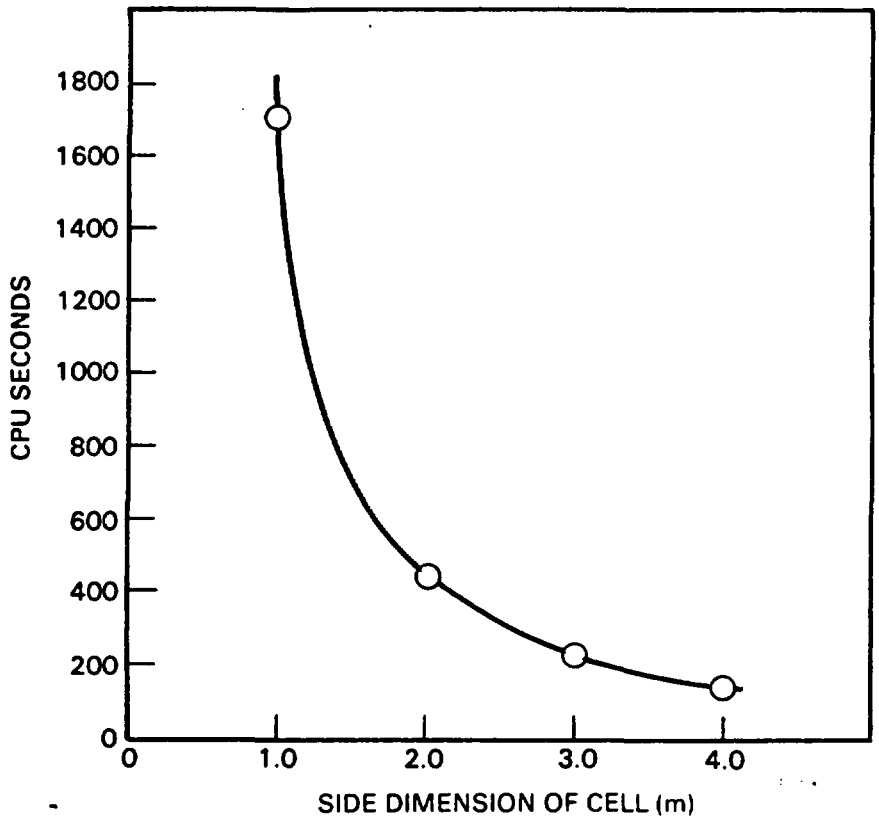


FIGURE B.8. Computational Time in Central Processing Unit Versus Side Dimension of the Cell for Investigation of Proper Grid Spacing

simulations and decreased rapidly with the number of elements. TRUST applies an iterative solution scheme to a system of mixed implicit-explicit elements (Reisenauer et al., 1982). Consequently, the total number of iterations required in a particular problem was used to reflect magnitude of the discretization error. The discretization error is the difference between exact and numerical solutions to the partial differential equation for flow; this error should be kept to a minimum. By considering the number of iterations per cell, the analysis was normalized for variable mesh size.

Results of the analysis (Fig. B.8 to B.10) indicated that a maximum side dimension for the cells between 1.5 and 2.5 m was satisfactory.

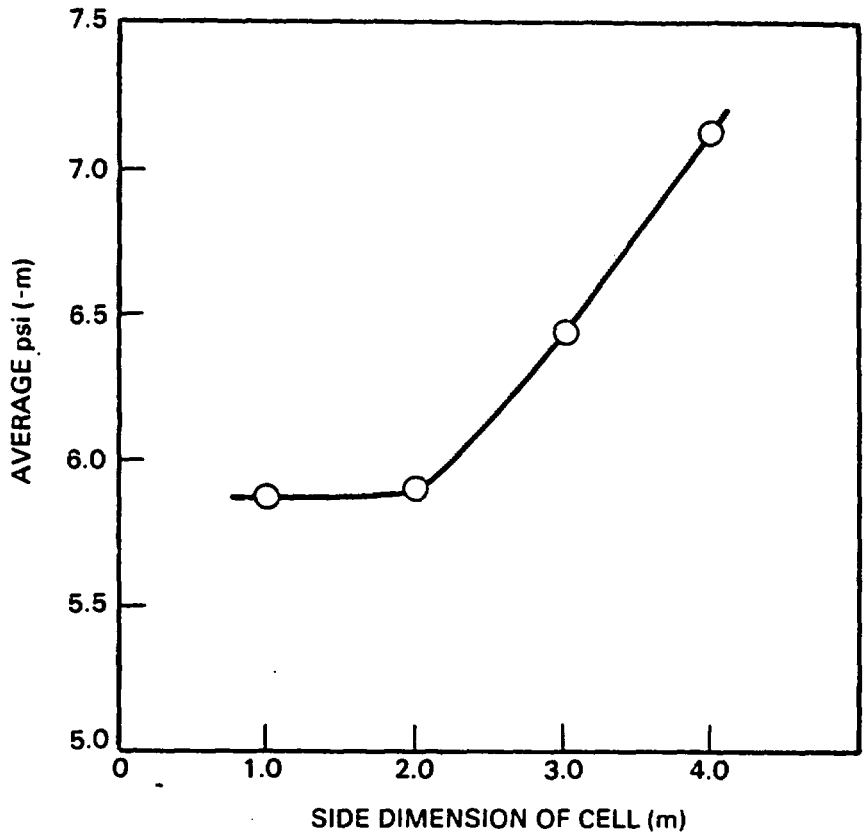


FIGURE B.9. Average Pressure Head over the Square Versus Side Dimension of the Cell for Investigation of Proper Grid Spacing

BOUNDARY CONDITIONS

Boundary conditions were the same for analyses of the repository drifts and vertical shaft: flux on the upper boundary, prescribed hydraulic head at the lower boundary, and no-flow vertical boundaries. The boundary conditions were based on the assumption that the predominant hydraulic gradient is vertically downward in Yucca Mountain.

The upper boundary was modeled as prescribed flux, representing recharge to the flow system. Recharge of water to the system at the upper boundary was assumed to be 0.4 cm/yr. This number is approximately 2 percent of the rainfall at the surface of Yucca Mountain (Roseboom 1983; Sinnock et al. 1984). Detailed calculations by Rice (1984) support recharge values within this range.

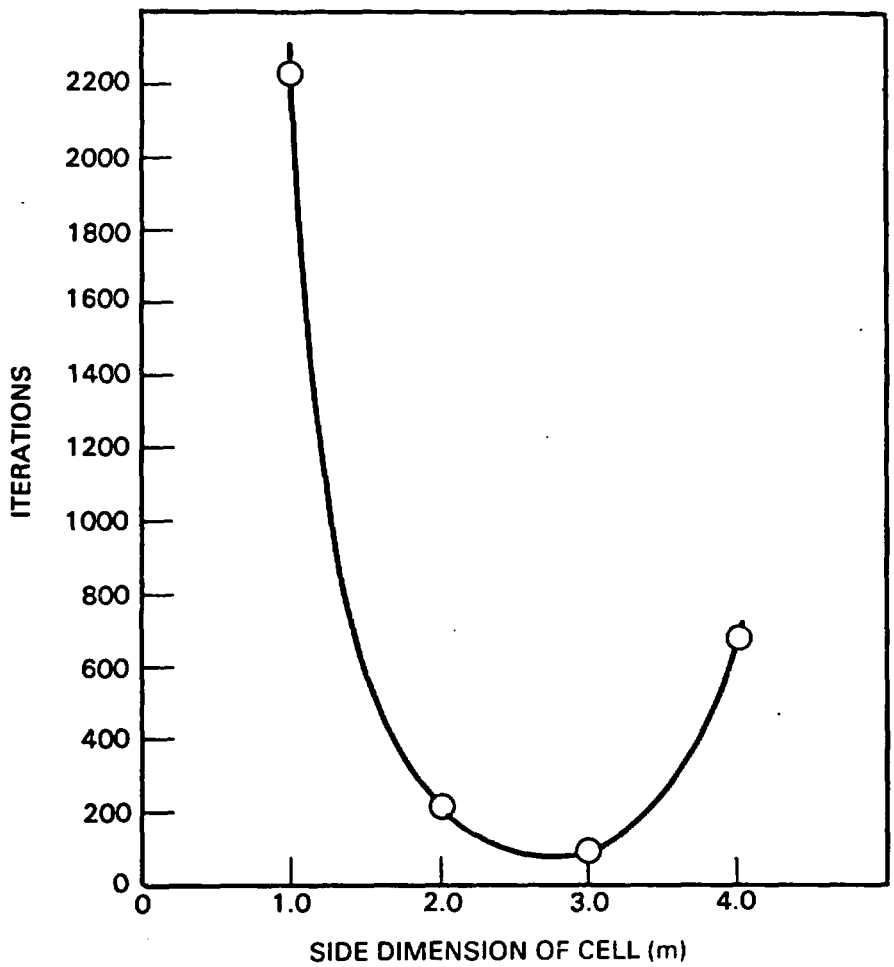


FIGURE B.10. Total Number of Iterations Versus Side Dimension of the Cell for Investigation of Proper Grid Spacing

To avoid modeling from the potential repository to the water table, a lower boundary was modeled in a manner that allowed drainage to occur in response to the amount of water reaching the lower boundary. To construct a drainage condition, the lower boundary was modeled as prescribed hydraulic head. The prescribed head was specified such that a gradient existed between the boundary node and adjacent interior node. Flow occurred in response to this gradient as required to drain the profile, and at steady state, the flux predicted by the gradient boundary condition was equal to the prescribed flux

at the upper boundary. In all cases, the lower boundary was placed at a sufficient distance from the region of interest so as not to influence results.

STARTING ESTIMATES OF PRESSURE HEAD

For most of the simulations, the starting estimate of pressure head in the volcanic tuffs was at -10.0 m. The solution of interest for the test cases was steady state so that the starting estimate was chosen close to the predicted final pressure heads to minimize computational effort.

The TRUST code was used to simulate the transient case to arrive at steady state. Steady state was assumed to be reached when the difference between flux at the upper and lower boundaries was less than several percent. For the most part, transient results were not considered in the repository sealing investigations.

APPENDIX C

ANALYSIS OF A REPOSITORY DRIFT

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ANALYSIS OF A REPOSITORY DRIFT

Investigation of the repository drift included analyses of both horizontal and vertical emplacement of waste packages. Horizontal emplacement of waste packages requires mining significantly less material than that required for vertical emplacement (Scully et al. 1984). The emplacement schemes were analyzed in only two dimensions for the repository sealing investigations.

HORIZONTAL EMPLACEMENT OF WASTE PACKAGES

The planned horizontal emplacement scheme involves placing waste packages horizontally into long tubes protruding from the sidewall of the repository drift (Fig. C.1). The center of the repository drift forms a plane of symmetry and is a no-flow boundary; holes for emplacement of waste packages extend out on either side. The right boundary of the flow region was placed 4.6 m into the waste packages and is also a no-flow boundary. Tuff sample S-19 (Gee 1982)[a] was used to represent the surrounding host rock formation. Clay and sand were considered as backfill in the waste-package hole and repository drift. In addition to the waste packages themselves, the concrete plugs were assumed to be impermeable.

The preliminary results of simulating horizontal emplacement of waste packages (Fig. C.1) indicated that, if detailed results near the waste packages are desired, the problem should be modeled in three dimensions rather than two dimensions. Modeling the flow system with the two-dimensional cross section forced water to flow through the emplacement tube. More likely, water flows around the waste package and emplacement tube in the third dimension. However, because the primary goal of these calculations was to assess the effect of different backfill materials on flow near the waste packages, it was determined

(a) Gee, G. W. 1982. Laboratory Report on the Unsaturated Flow Characteristics of Core Samples from Nevada Test Site Well USW GU-3, Interim Status Report to SNL from PNL, October, 65 p.

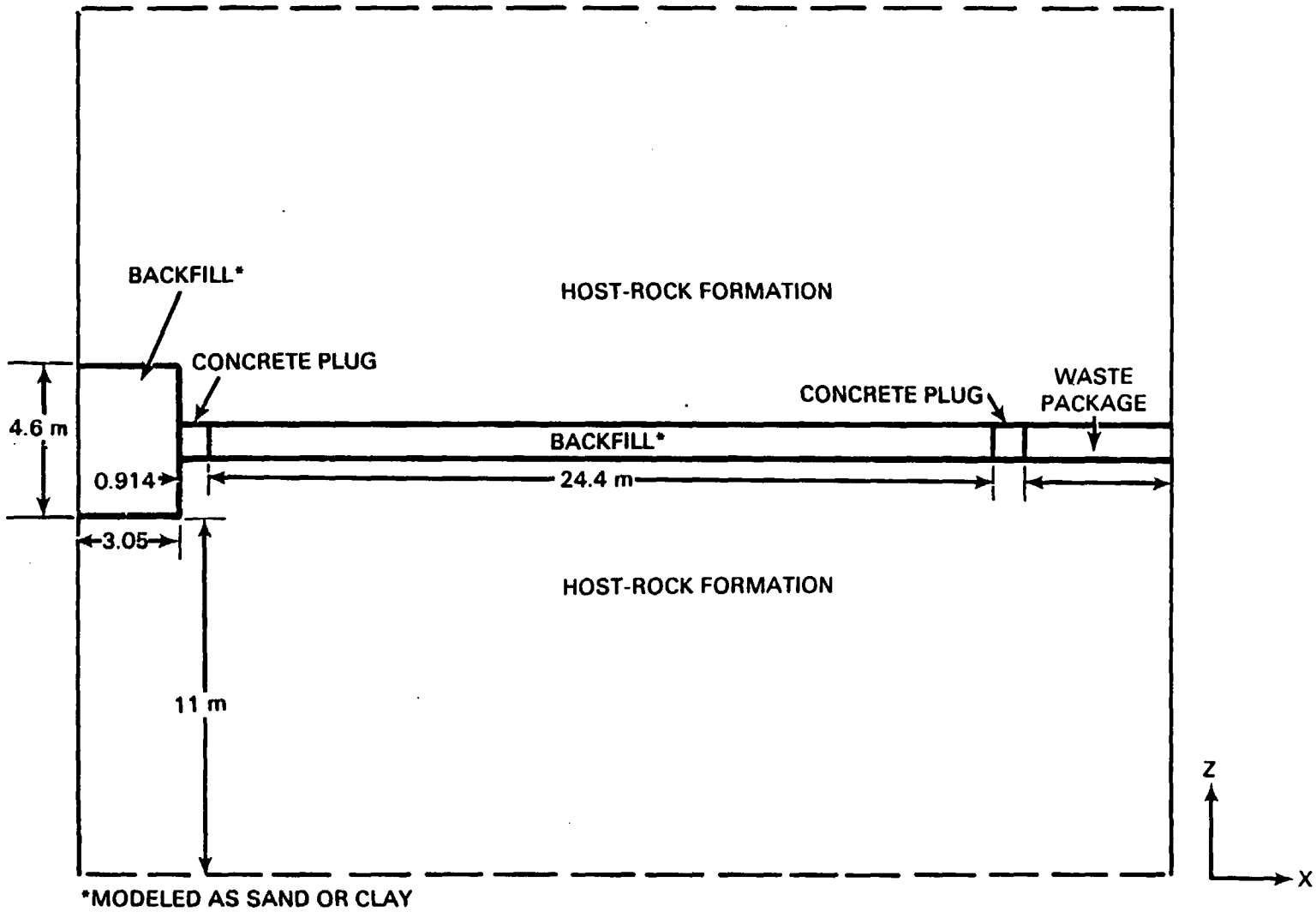


FIGURE C.1. Configuration for Analysis of the Repository Drift with Horizontal Emplacement of Waste Packages

that results from the vertical emplacement analysis could be extrapolated to the horizontal case. Hence, the horizontal emplacement analysis was not continued.

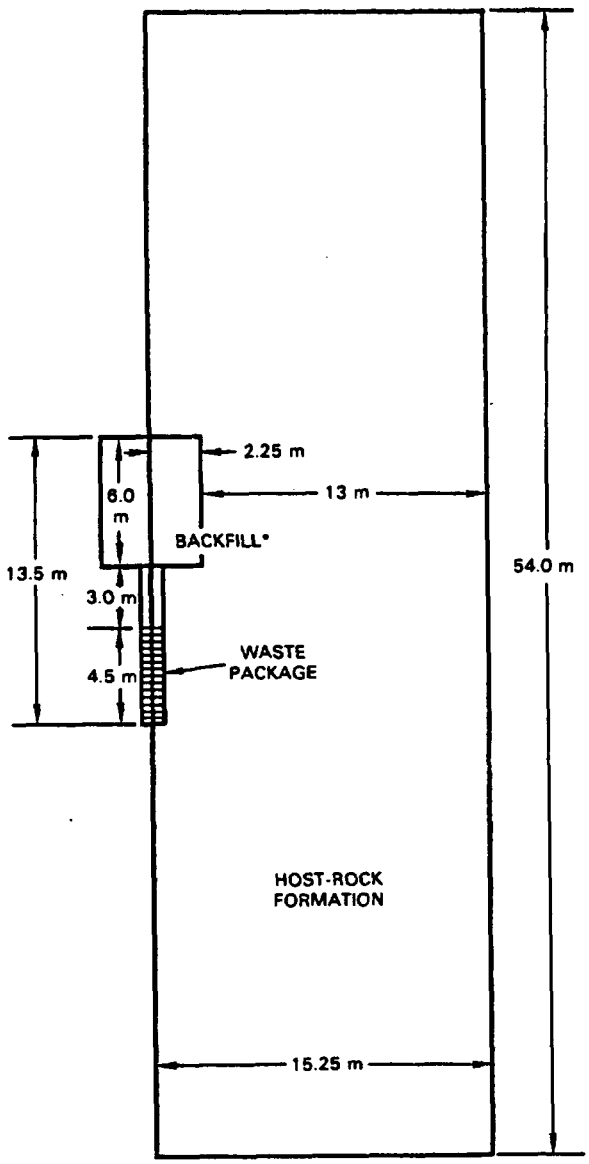
VERTICAL EMPLACEMENT OF WASTE PACKAGES

The planned vertical emplacement scheme consists of placing individual waste packages into holes in the floor of the repository drifts. A cross section of the scheme for vertical emplacement of waste packages is illustrated in Figure C.2. Two vertical planes of symmetry were used to define the flow region: one created by the centerline of the drift and waste-package hole, and the other by the centerline between drifts. The drift was assumed to be backfilled with a range of crushed-tuff materials that was modeled by sand or clay; the waste package was considered to be impermeable. Upper and lower boundaries were positioned at a sufficient distance to prevent influence of flow near the waste package and drift.

The integrated finite difference grid used to model the vertical waste canister emplacement scheme is illustrated in Figure C.3.

Four cases were investigated for the repository drift with vertical emplacement of waste canisters. To consider the effects of backfill materials, tuff sample S-19 (Gee 1982) was used to simulate the host-rock formation with sand or clay modeled as backfill. The effect of permeability of the host-rock formation was investigated with two cases. The first case consisted of tuff sample S-19 modeled as the host rock, with the saturated permeability increased and clay backfill in the drift. The second case consisted of tuff sample S-19 modeled as the host rock, with the saturated permeability decreased and clay simulated as backfill.

Response of the system trending to steady state from the starting estimate of pressure head is illustrated in Figure C.4. Because TRUST was used to simulate through the transient case to reach steady state, time was included as the independent variable in Figure C.4. However, when analyzing the results, time should only be considered as a measure of iterations required to arrive at steady state. After an initially rapid change, steady-state conditions were approached asymptotically (Fig. C.4).



*MODELED AS SAND OR CLAY

FIGURE C.2. Configuration for Analysis of the Repository Drift with Vertical Emplacement of Waste Packages

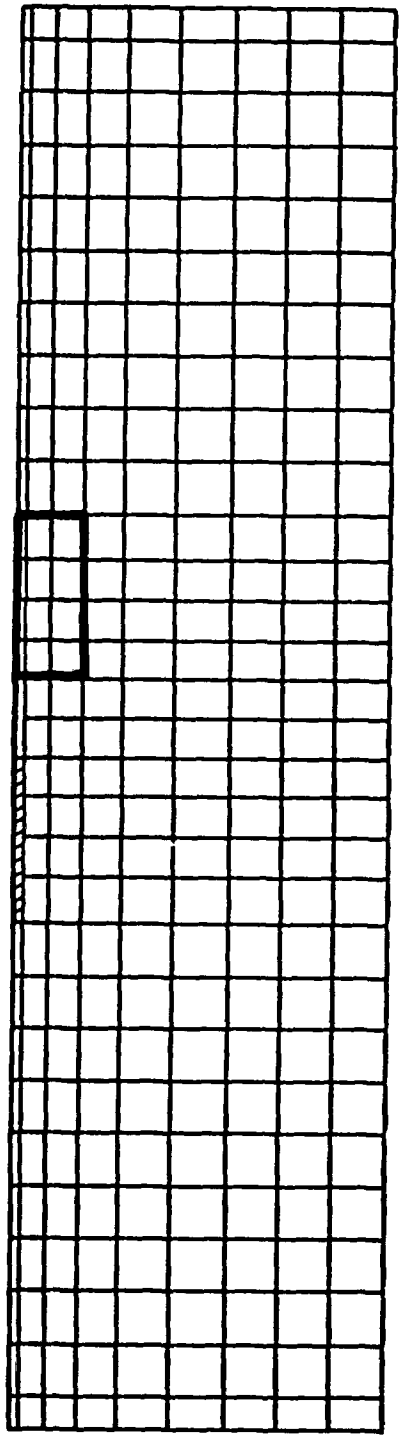


FIGURE C.3. IFD Grid for the Repository Drift with Vertical Emplacement of Waste Packages

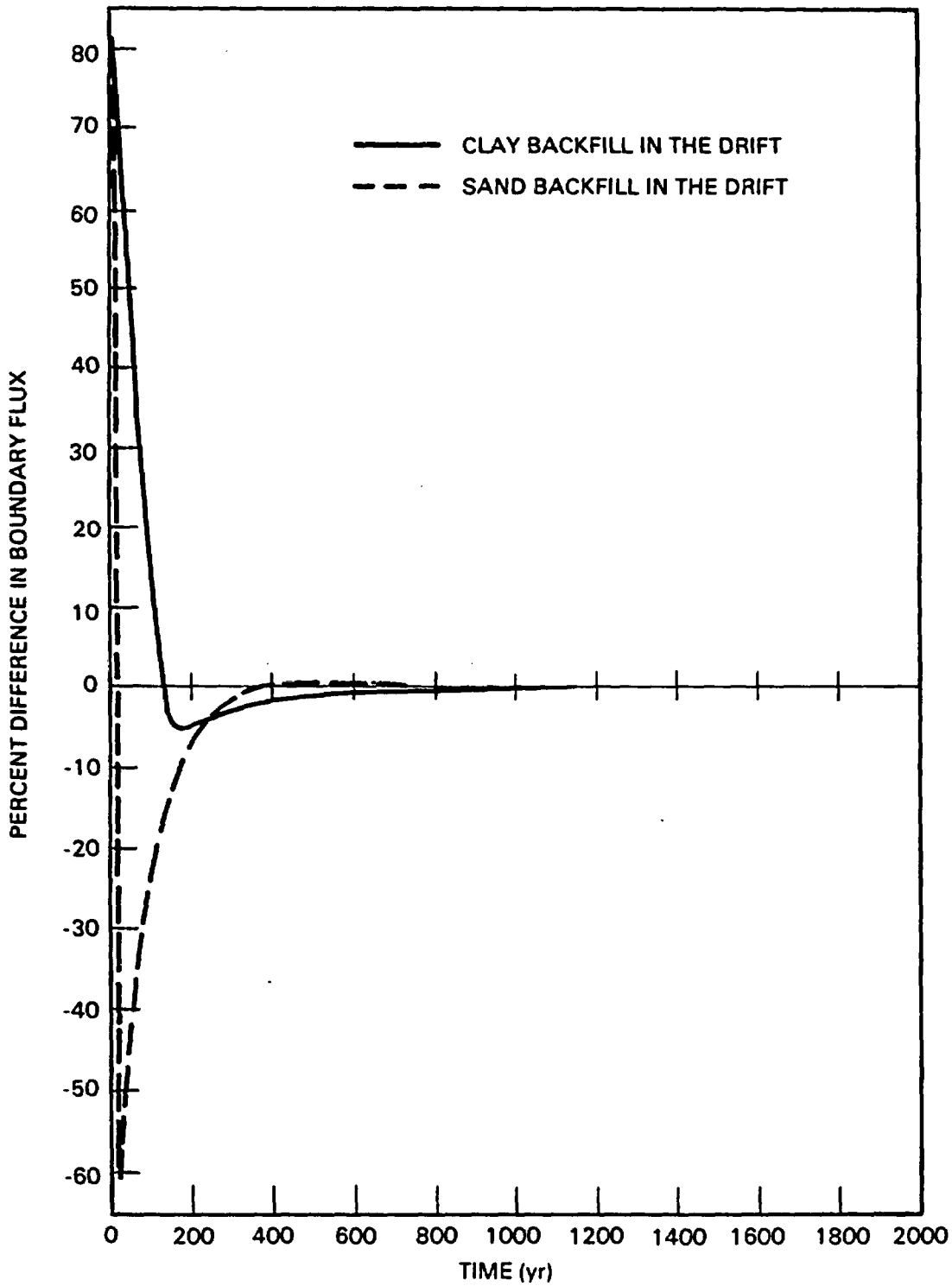


FIGURE C.4. Percent Difference Between Inflow and Outflow Versus Time for the Repository Drift with Vertical Emplacement of Waste Packages and Clay and Sand Backfill in the Drift

The results comparing the repository drift with sand and clay backfill are illustrated in Figures C.5 through C.10. Figures C.5 and C.6 illustrate the distributions of moisture content at steady state for the repository drift with clay and sand backfill, respectively. Figure C.7 illustrates the steady-state distribution of hydraulic head for clay backfill in the drift; Figure C.8 illustrates the approximate steady-state distribution of hydraulic head for sand backfill. The term 'approximate' is used because the results illustrated in Figure C.8 are close to but not completely at steady state, as indicated by the closed hydraulic-head contours in the drift. However, as indicated in Table C.1, permeability near the center of the drift with sand backfill is over 10 orders of magnitude smaller than that of the surrounding host rock. Because of the extremely low permeability in the drained sand, a large amount of simulation time would be required to completely reach steady state. The results are sufficiently close to steady state that they are not expected to change. Figures C.9 and C.10 are the pathlines at steady state and approximate steady state for both clay and sand backfill, respectively.

Results comparing the repository drift in host rock with both increased and decreased permeability are illustrated in Figures C.11 through C.14. Figures C.11 and C.12 illustrate the steady-state distributions of moisture content for the respective cases of decreased and increased permeability of the host rock. The perturbations to permeability of sample S-19 are listed in Table B.1. Figures C.13 and C.14 are the pathlines at steady state corresponding to the decreased and increased host-rock permeability.

Flow rates past the vertical waste package in cases investigated for the repository drift are listed in Table C.2. The flow rates are given for the stippled element illustrated in Figure C.15. A summary of water flow into the repository drift for vertical emplacement of waste packages is provided in Table C.3.

Discussion of Results for Analysis of Vertical Emplacement of Waste Packages

Results of simulating vertical emplacement of waste packages demonstrated the difference between using coarse and fine materials for backfill in the repository drift. Figures C.5 and C.6 illustrate that sand drained more completely, indicated by the lower moisture contents in the drift in Figure C.6,

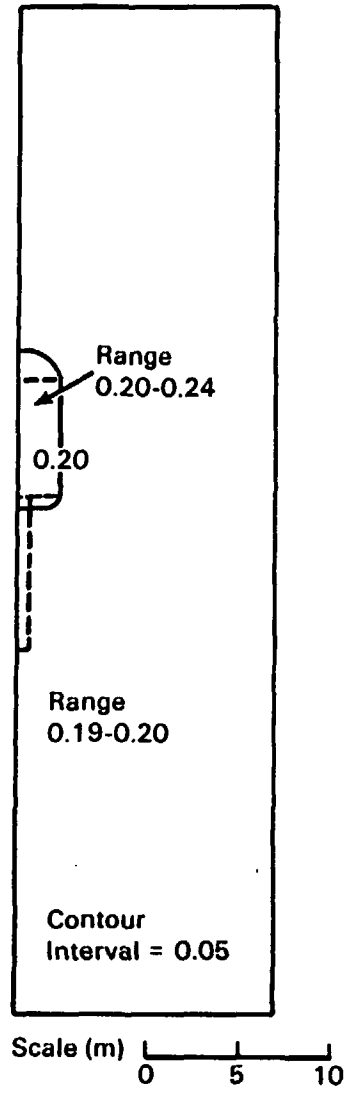


FIGURE C.5. Distribution of Moisture Content at Steady State for the Repository Drift with Vertical Emplacement of Waste Packages and Clay Backfill in the Drift

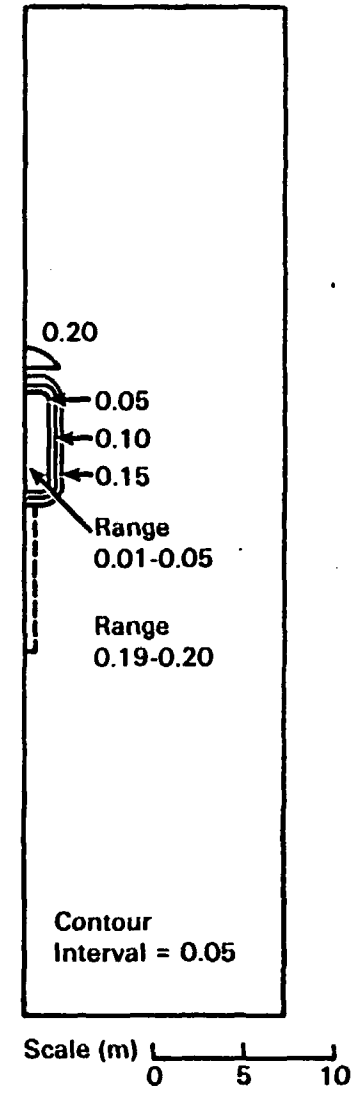


FIGURE C.6. Distribution of Moisture Content at Approximate Steady State for the Repository Drift with Vertical Emplacement of Waste Packages and Sand Backfill in the Drift

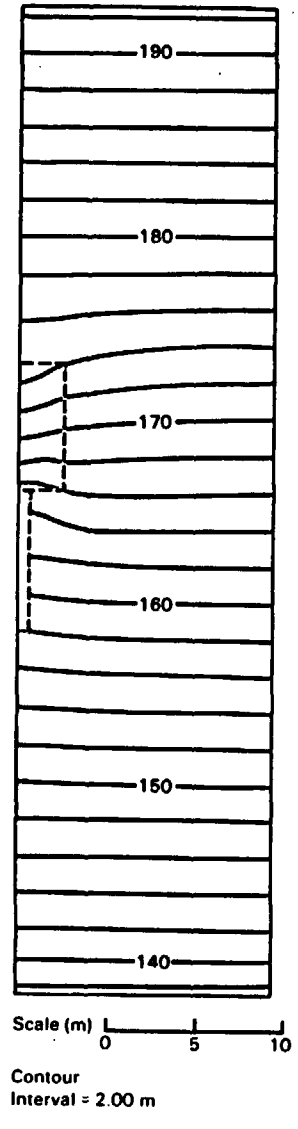


FIGURE C.7. Steady-State Distribution of Hydraulic Head (m) for the Repository Drift with Vertical Emplacement of Waste Packages and Clay Backfill in the Drift

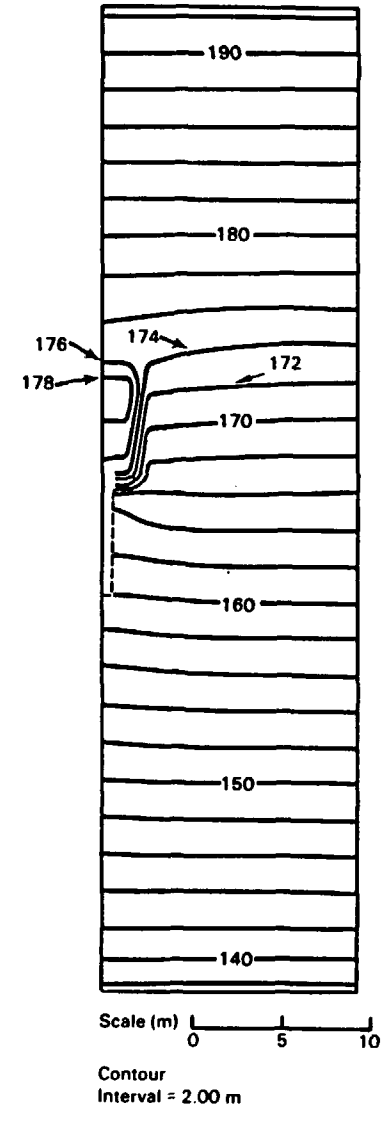


FIGURE C.8. Approximate Steady-State Distribution of Hydraulic Head for the Repository Drift with Vertical Emplacement of Waste Packages and Sand Backfill in the Drift

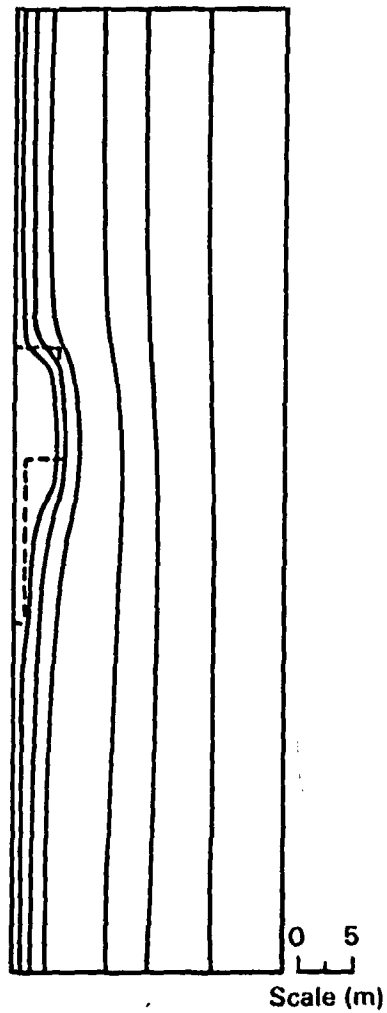


FIGURE C.9. Pathlines at Steady State for the Repository Drift with Vertical Emplacement of Waste Packages and Clay Backfill in the Drift

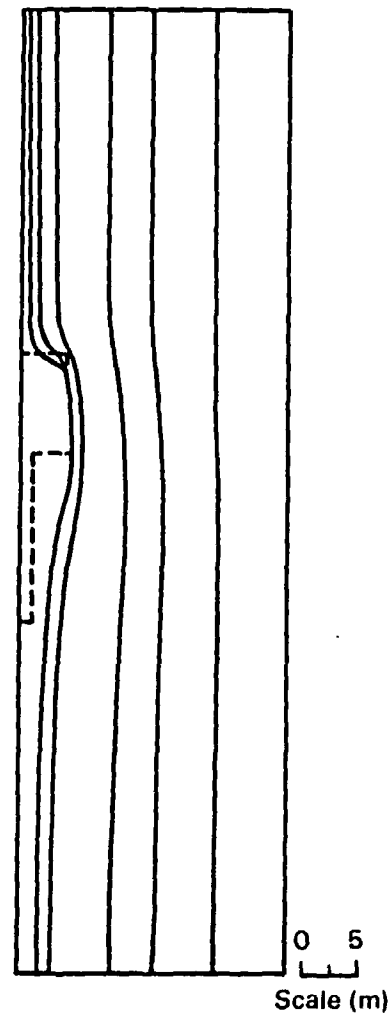


FIGURE C.10. Pathlines at Approximate Steady State for the Repository Drift with Vertical Emplacement of Waste Packages and Sand Backfill in the Drift

TABLE C.1. Permeabilities near the Center of the Repository Drift in Cases Investigated for Vertical Emplacement of Waste Packages

Case	Permeability, m^2
Tuff Sample S-19, Clay Backfill	1.09×10^{-19}
Tuff Sample S-19, Sand Backfill	8.76×10^{-33}
Tuff Sample S-19 with Increased Permeability, Clay Backfill	7.98×10^{-21}
Tuff Sample S-19 with Decreased Permeability, Clay Backfill	1.03×10^{-17}

while clay retained moisture. The drained sand backfill formed a capillary barrier to water flow as indicated in Figure C.10. The steady-state pathlines in Figure C.10 are distorted farther away from the drift than those in Figure C.9.

Comparison of the permeability of different backfill materials for the repository drift (see Table C.1) illustrates the concept of a capillary barrier. The permeability in the drift backfilled with sand is much lower than in the drift backfilled with clay at steady-state conditions. Further, the sand is more completely drained than the clay.

Increasing permeability of the host rock produced little effect on flow through the repository drift, as illustrated in Figures C.12 and C.14. However, decreasing the host-rock permeability to an order of magnitude below that of the clay backfill caused the drift to remain at much higher saturation (see Figure C.11). At higher saturation in the host rock with decreased permeability (99 percent), water flow past the waste package increased an average of 66 percent (average of fluid flow into and out of the stippled element listed in Table C.2), and water flow into the repository drift increased by two orders of magnitude (see Table C.3). The permeability in the backfill also increased by several orders of magnitude for the case of decreased host-rock permeability (Table C.1). Although we did not simulate coarse backfill in the case with decreased host-rock permeability, at the approximately -1.0 m pressure head in the drift, sand backfill would be drained (see Fig. B.5 and B.6) and would act as a capillary barrier.

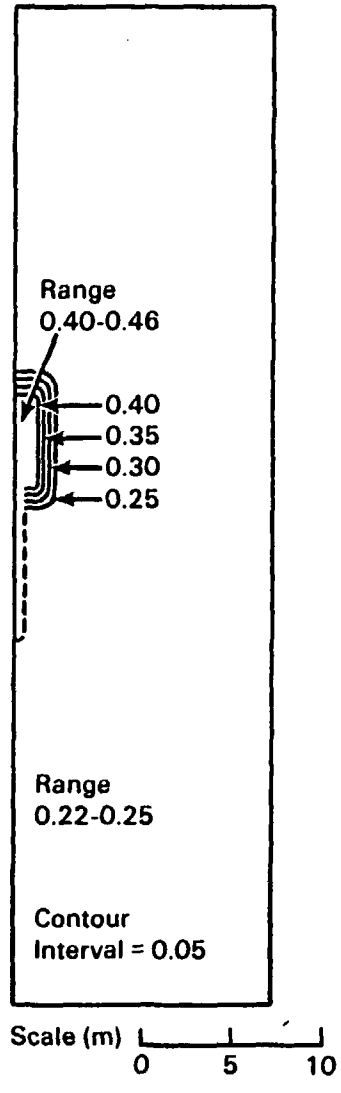


FIGURE C.11. Distribution of Moisture Content at Steady State for the Repository Drift with Vertical Emplacement of Waste Packages, Clay Backfill, and Decreased Host-Rock Permeability

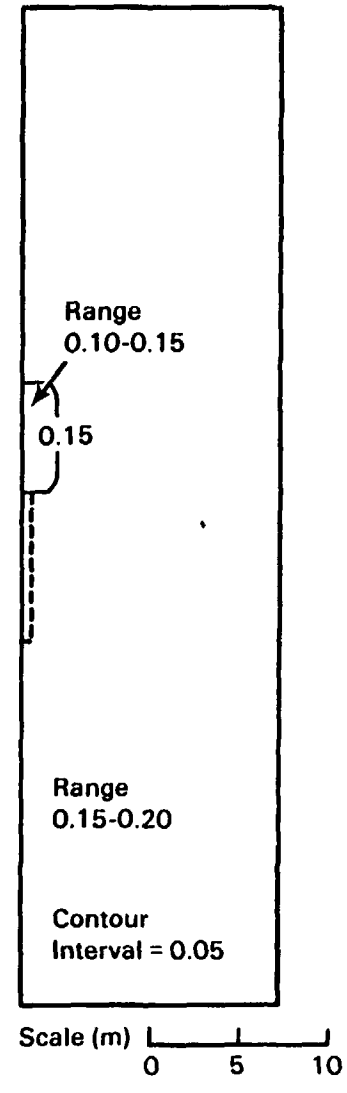


FIGURE C.12. Distribution of Moisture Content at Steady State for the Repository Drift with Vertical Emplacement of Waste Packages, Clay Backfill, and Increased Host-Rock Permeability

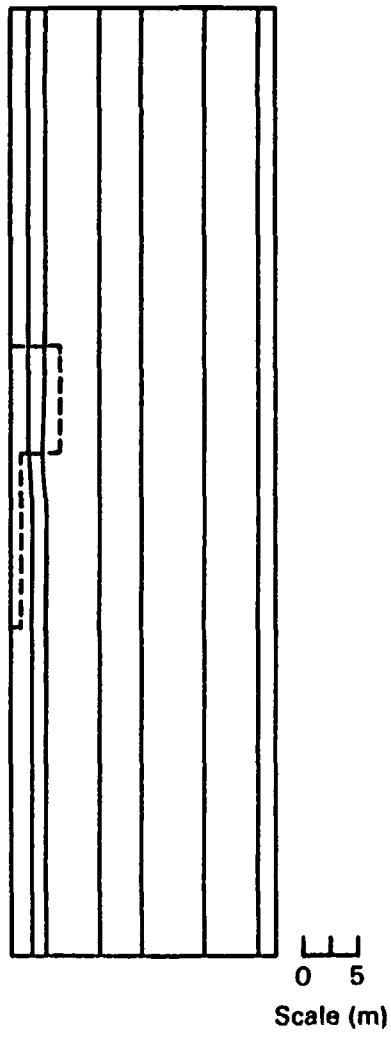


FIGURE C.13. Pathlines at Steady State for the Repository Drift with Vertical Emplacement of Waste Packages, Clay Backfill, and Decreased Host-Rock Permeability

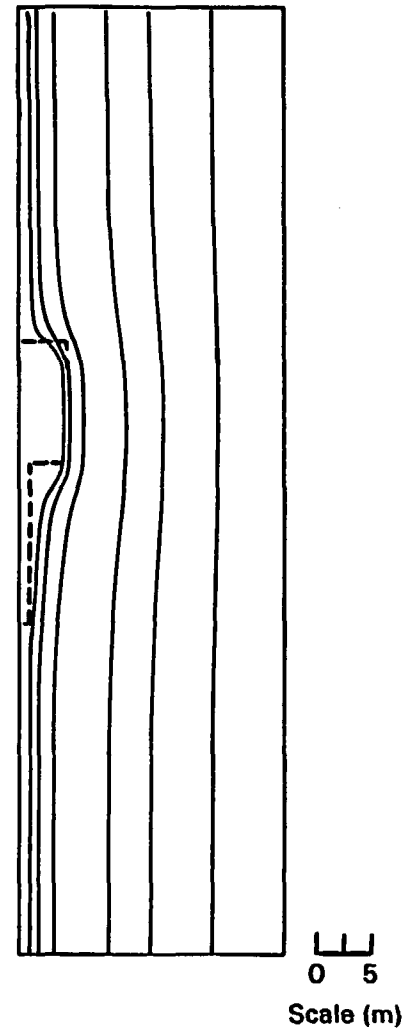


FIGURE C.14. Pathlines at Steady State for the Repository Drift with Vertical Emplacement of Waste Packages, Clay Backfill, and Increased Host-Rock Permeability

TABLE C.2. Flow Rates Past the Vertical Waste Package (through the Stippled Element in Figure C.15) for the Repository Drift

Case	Fluid Flow in the Vertical Direction Past the Waste Package (m^3/day)
Tuff Sample S-19, Clay Backfill	3.70×10^{-6}(a) 4.21×10^{-6}(b)
Tuff Sample S-19, Sand Backfill	3.61×10^{-6}(a) 4.15×10^{-6}(b)
Tuff Sample S-19 with Increased Permeability, Clay Backfill	4.81×10^{-6}(a) 5.22×10^{-6}(b)
Tuff Sample S-19 with Decreased Permeability, Clay Backfill	6.64×10^{-6}(a) 6.47×10^{-6}(b)

(a) Fluid flow into the stippled element.
(b) Fluid flow out of the stippled element.

TABLE C.3. Summary of Water Flow into the Repository Drift with Vertical Emplacement of Waste Packages

Case	Fluid Flow into the Drift as a Percent of Influx(a)
Tuff Sample S-19, Clay Backfill	0.55
Tuff Sample S-19, Sand Backfill	0.0
Tuff Sample S-19 with Increased Permeability, Clay Backfill	0.26
Tuff Sample S-19 with Decreased Permeability, Clay Backfill	16.56

(a) Influx = $1.671 \times 10^{-4} m^3$/day and is the product of flux (0.4 cm/yr), width (15.25 m) and depth of the modeled region (1 m)

In the repository drift, with vertical emplacement of waste packages, diversion of flow around the drifts did not extend far into the host rock (see Fig. C.9, C.10, C.13, and C.14). Consequently, backfill in the drift will not

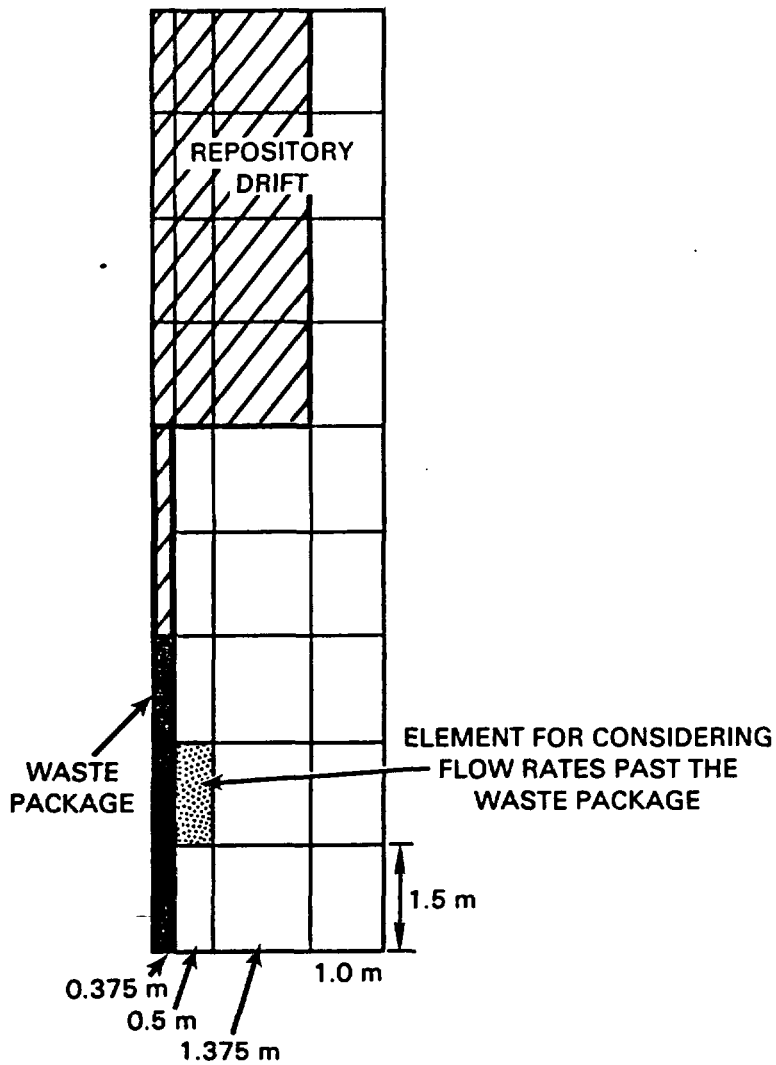


FIGURE C.15. Enlargement of the IFD Grid near the Repository Drift with Vertical Emplacement of the Waste Package

influence flow around horizontally emplaced waste packages. However, it may be possible to place backfill around the waste packages to divert flow, but an investigation of the waste packages is beyond the scope of this repository sealing study.

APPENDIX D

ANALYSIS OF THE VERTICAL REPOSITORY SHAFT

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A number of vertical and inclined penetrations to the level of the repository are planned for Yucca Mountain. The penetrations include vertical boreholes for exploration and testing, vertical shafts for testing and repository development, as well as inclined ramps for repository development and possible testing. The analysis described in this appendix considers backfilling a vertical shaft. The results may be useful for vertical boreholes as well.

Investigation of backfilling the vertical repository shaft involved modeling a shaft intersected by a contact between volcanic tuff units (Fig. D.1). The stratigraphic contact was assumed to be dipping 8 degrees to the east as interpreted from Figure 2. The intent of the repository shaft analysis was to investigate the effects of contrasting porosity and permeability across a formation interface; a key part of the investigation was to determine whether a perched water table developed.

Analysis of the vertical repository shaft was strongly three-dimensional in nature; however, the two-dimensional representation (see Fig. D.1) was considered to make the preliminary calculations conservative by forcing water to flow into the shaft, while it would more likely flow around.

The integrated finite difference (IFD) grid used to model the vertical repository shaft is illustrated in Figure D.2. Vertical boundaries were assumed to be at a sufficient distance so as not to influence water flow near the shaft.

Five configurations, which are summarized in Table D.1, were used to analyze the vertical shaft. As indicated earlier in Appendix B, sample S-4 is welded volcanic tuff, and samples S-14 and S-17 are nonwelded tuffs. The configurations in Table D.1 represent possible combinations of welded and nonwelded tuffs in Yucca Mountain.

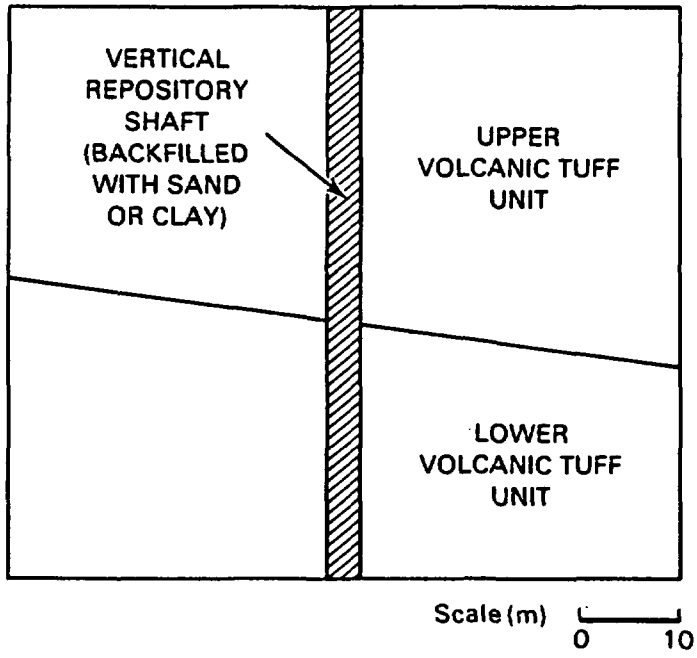

FIGURE D.1. Configuration for Analysis of the Vertical Repository Shaft

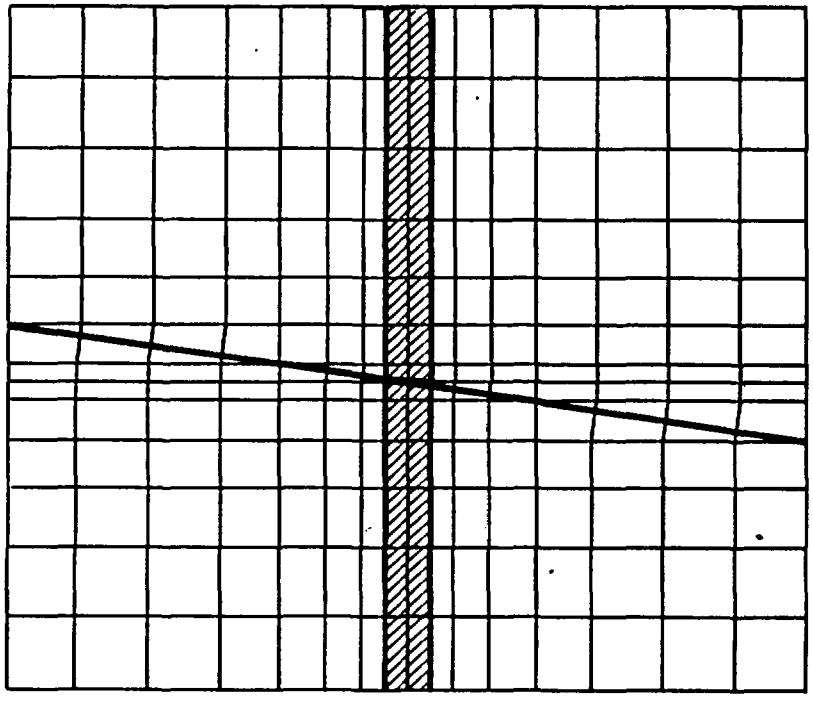

FIGURE D.2. IFD Grid for Analysis of the Vertical Repository Shaft

TABLE D.1. Summary of Cases for Analysis of a Vertical Repository Shaft

Case	Upper Volcanic Tuff Unit[a]	Lower Volcanic Tuff Unit[a]	Backfill Material
1	S-4	S-17	clay
2	S-4	S-17	sand
3	S-17	S-4	clay
4	S-17	S-4	sand
5	S-4 (k_s increased)	S-14 (k_s decreased)	clay (k_s decreased)

(a) Sample S-4 is welded volcanic tuff; S-14 and S-17 are nonwelded tuff.

An initial guess of pressure head at -10.0 m was assumed for the host-rock formations in cases 1 through 4 listed in Table D.1. An initial guess of pressure head at -1.0 m was assumed for Case 5. All cases were continued to steady state.

None of the simulated cases produced a perched water table above the interface between tuff units at steady state. However, a buildup of water occurred during the transient stage of Case 5, as indicated by the contours of pressure head in Figure D.3. This water buildup disappeared as the solution approached steady state. Inflow to the vertical repository shaft at steady state is summarized in Table D.2. Steady-state distributions of moisture content for Cases 1 and 2 are illustrated in Figures D.4 and D.5, respectively. Steady-state distributions of pressure head for Cases 1 and 2 are illustrated in Figures D.6 and D.7, respectively.

DISCUSSION OF RESULTS FOR ANALYSIS OF THE VERTICAL REPOSITORY SHAFT

In the modeling investigation of the vertical repository shaft, a perched zone at the formation interface occurred only as a transient phenomenon. This occurred primarily because of the selection of initial conditions and the conceptual model used. Prediction of perched water by the model also suggests that the steady-state approach may not be adequate for modeling all aspects of

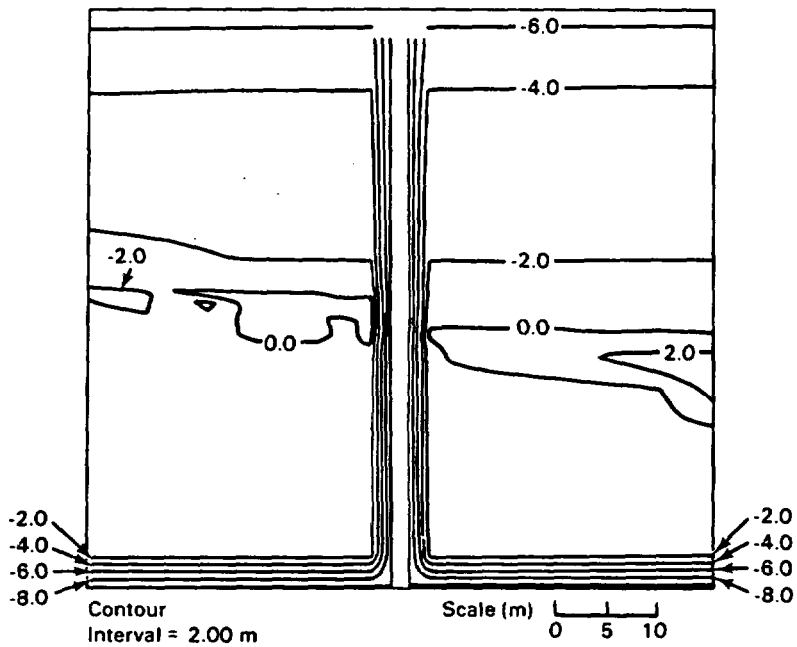

FIGURE D.3. Distribution of Pressure Head at a Transient Stage of Simulation for Analysis of the Vertical Repository Shaft with Clay Backfill and Tuff Sample S-4 Overlying Sample S-14 (Case 5)

TABLE D.2. Summary of Steady-State Water Flow Entering the Vertical Repository Shaft for All Cases Considered

Case	Flow into the Shaft as a Percent of Total Inflow to the Modeled Region[a]
1	1.25
2	0.0003
3	1.25
4	0.0003
5	0.02

(a) Inflow = 7.031×10^{-4} m^3/day for the vertical repository shaft.

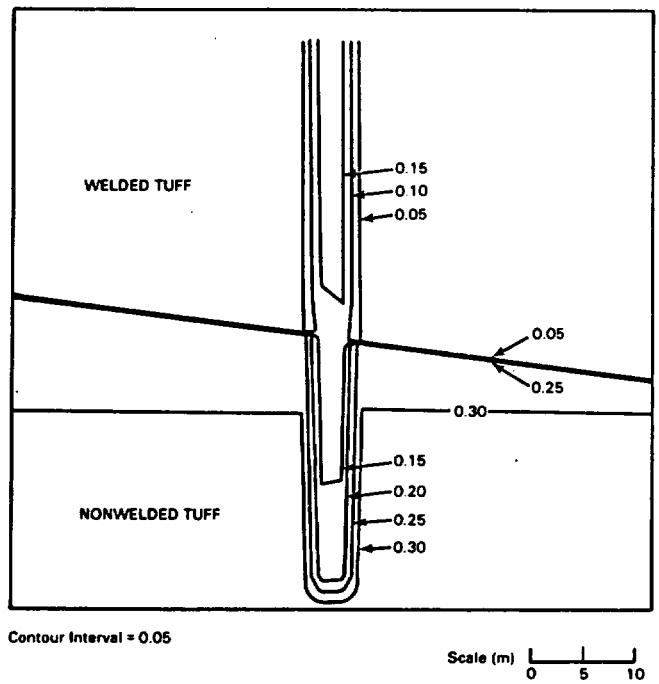

FIGURE D.4. Distribution of Moisture Content at Steady State for Case 1 (Table D.1) in the Analysis of the Vertical Repository Shaft

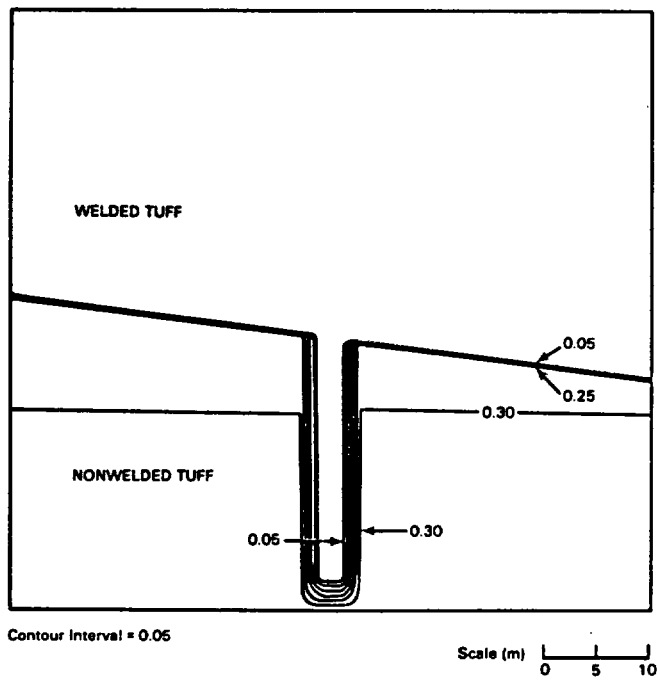

FIGURE D.5. Distribution of Moisture Content at Steady State for Case 2 (Table D.1) in the Analysis of the Vertical Repository Shaft

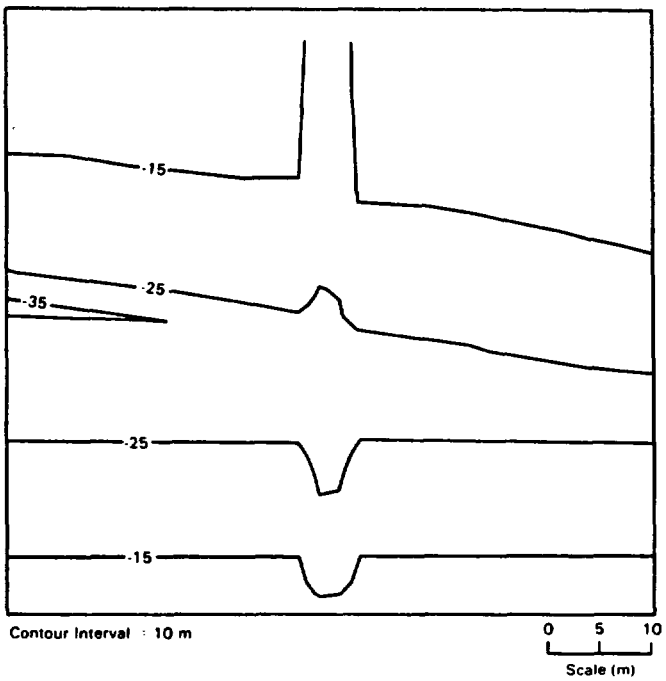

FIGURE D.6. Distribution of Pressure Head at Steady State for Case 1 (Table D.1) in the Analysis of the Vertical Repository Shaft

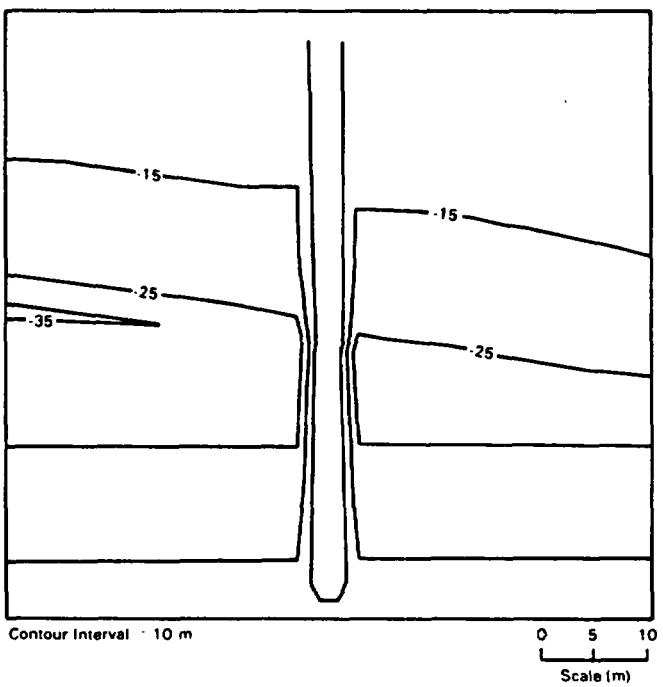

FIGURE D.7. Distribution of Pressure Head at Steady State for Case 2 (Table D.1) in the Analysis of the Vertical Repository Shaft

sealing a repository in unsaturated volcanic tuff and transient analyses should be considered if field evidence of perched water at material interfaces is found. Currently, no field evidence of extensive perched water exists within the primary area of the prospective repository (DOE 1984).

Steady-state flow rates into the shaft (see Table D.2) illustrate the difference between backfill materials rather than orientation of the welded and nonwelded tuff units (see Table D.1). Although flow rates are small, differences between the cases cover several orders of magnitude. Results in Table D.1 indicate that configuration of welded and nonwelded tuff above or below the stratigraphic contact did not influence flow rates into the shaft. Flow into the vertical shaft depends on moisture content of the backfill material; the coarse backfill drains more completely (see Fig. D.5 and D.7) than the fine-grained material, which retains moisture (see Fig. D.4 and D.6) and allows water to flow into the shaft. This comparison supports the concept that coarse backfill behaved as a capillary barrier.

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