NUMERICAL ANALYSES TO EVALUATE BACKFILLING REPOSITORY DRIFTS IN UNSATURATED TUFF[a]

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ABSTRACT

Preliminary numerical analyses were performed to determine if the choice of drift backfill could influence water flow past waste packages adjacent to a repository drift in unsaturated volcanic tuff. These numerical analyses for a prospective nuclear-waste repository in Yucca Mountain located on and adjacent to the Nevada Test Site consisted of unsaturated flow modeling using the computer code TRUST. An idealized configuration of a repository drift with vertical emplacement of waste packages was evaluated, considering both fine and coarse materials as backfill in the drift. In the numerical simulations, coarse-grained material drained more completely than fine-grained material and formed a more effective capillary barrier to water flow in the unsaturated medium of the repository horizon. Although the magnitude of flow in the modeled regions is small, backfill material was shown to influence flow inside a repository drift. However, the numerical analyses demonstrate that selection of backfill does not significantly influence water flow past vertically emplaced waste packages for the conditions simulated.

INTRODUCTION

The Nevada Nuclear Waste Storage Investigations (NNWSI) project, managed by the Nevada Operations Office of the U.S. Department of Energy (DOE), has the responsibility for evaluating the feasibility of siting a repository in volcanic tuff 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 arid region of the United States. Key considerations for siting a nuclear waste repository at Yucca Mountain are the partially saturated (unsaturated) conditions of the volcanic tuff host rock and the limited quantity of water movement that is typically believed to occur through thick unsaturated zones of the desert environment.[1]

As part of the evaluation of Yucca Mountain for suitability as a nuclear waste repository, Sandia National Laboratories (SNL) has the responsibility to investigate methods and materials for sealing the potential repository and entrance shafts and to develop appropriate seal designs. To assist in the investigation of sealing the repository, hydrologic calculations were performed by the Pacific Northwest Laboratory (PNL) (Freshley et al. 1985, in preparation).[c] The calculations described in this paper investigate water flow in the vicinity of vertically emplaced waste packages. As used in this paper, 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 repository. Although not explicitly addressed, the calculations can be used to gain insight into flow near drifts from which waste packages have been horizontally emplaced.

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

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Sealing a Repository in Unsaturated Tuff

As suggested by provisions in Section 134 of 10 CFR 60,[2,3] 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 engineered barriers could contribute to the performance of the waste package would be for the drift backfill to influence water flow in the vicinity

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[b] A U.S. DOE facility.

[c] Freshley, M. D., F. H. Dove and J. A. Fernandez. 1985. Hydrologic Calculations to Evaluate Backfilling Shafts and Drifts for a Prospective Nuclear Waste Repository in Unsaturated Tuff. SAND83-2465, (Draft Report). Prepared by Pacific Northwest Laboratory for Sandia National Laboratories, Albuquerque, New Mexico.

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 paper are designed to assess the influence of various backfill materials on the flow and moisture retention in the vicinity of waste packages.

In establishing rationale for the types of materials to be considered in the analyses, results of other researchers investigating performance of capillary barriers to unsaturated water flow in shallow subsurface disposal of low-level radioactive waste were evaluated.[4,5,6] In each of these studies, capillary barriers were shown to substantially reduce infiltration through near-surface waste-storage facilities. The analyses described in this paper extend the concept of capillary barriers to possible deep disposal of high-level radioactive waste in the unsaturated zone at Yucca Mountain.

MODEL ASSUMPTIONS

Unsaturated flow modeling of the prospective repository was done with the computer code TRUST,[7] which simulates water flow in porous media under unsaturated conditions. The basic philosophy for modeling was to assume a continuum approach to water flow in the matrix of the fractured tuff of Yucca Mountain. The flux in the rock media was assumed to be less than the saturated hydraulic conductivity of the matrix. Hence, it is reasonable to assume the fractures do not transmit water and they were not included in the analysis.

In addition to the continuum approach, other assumptions were made for simulating water flow in the vicinity of the prospective repository at Yucca Mountain as follows:

- Steady state was assumed to have been reached when the difference in flux into and out of the system was less than 5 percent.
- Results at long simulation times were assumed to represent steady state for the repository sealing investigations.
- The predominant hydraulic gradient driving the flow system is 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 simulated materials was not considered.

SUMMARY OF MODELING

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 ψ [L] and elevation head z [L], where z is the elevation above a datum. In the unsaturated zone, pressure head is negative because work is required to extract water from opposing 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 void volume 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 of each material.

In TRUST, the unsaturated flow system is described by the following generalization of Richards' equation:[7,8]

$$\nabla \cdot [K(\psi)\,\nabla\,(z + \psi)] = M_c(D\psi/Dt) \qquad (1)$$

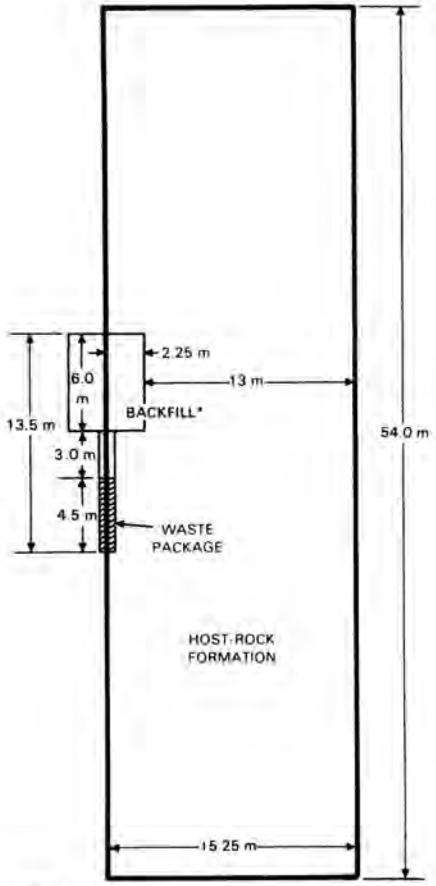
where ψ = pressure head
$K(\psi)$ = unsaturated hydraulic conductivity with dimensions of [L/T] as a function of pressure head
z = elevation head [L]
M_c = the fluid mass capacity
D/Dt = the material derivative.

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 integrated finite difference (IFD) form of Richards' equation is used in TRUST, where physical properties of the system are averaged over representative subdomains or elements. The derivation of mathematical equations and a description of the numerical implementation in TRUST are available in the sequence of papers by Narasimhan and Witherspoon[9,10] and Narasimhan et al.[8]

Model Input

Vertical emplacement of waste packages consists of placing individual waste packages into holes in the floor of the repository drifts, schematically illustrated in Fig. 1. 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 which were represented by sand or clay characteristics in the model; the waste package was considered to be impermeable.

Boundary conditions for the model 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, which is approximately 2 percent of the rainfall at the surface. Detailed calculations by Rice[11] support recharge values within this range. However, more recent interpretations of field data suggest that the percolation flux may be less than 0.01 cm/yr.[12] The lower boundary was modeled in a manner that allowed drainage to occur in response to the amount of water reaching the lower boundary. In all cases considered, both the upper and lower boundaries were positioned at a sufficient distance to prevent influence on flow near the waste package and drift. The vertical boundaries were considered to be impermeable as planes of symmetry.



*MODELED AS SAND OR CLAY

Fig. 1. Region considered for analysis of the repository drift with vertical emplacement of waste packages.

The hydraulic characteristics for materials used to represent the volcanic tuff units are from Gee (1982)[d] and Peters et al.[13] We used an analytical model developed by Mualem[14] based on the shape of measured moisture retention characteristics to calculate unsaturated hydraulic conductivity of the materials. As required for input to TRUST, the hydraulic conductivities [L/T] were converted to unsaturated permeabilities [L^2] which are a function of the medium alone by scaling the fluid properties.

Hydraulic properties for Chino clay and Crab Creek sand used to bound the effects of coarse-grained and fine-grained backfill in the drift were selected from Mualem.[15] The Chino clay was selected to represent the limiting case for fine-grained backfill, and the Crab Creek sand was used to simulate coarse-grained backfill that drains rapidly.

The moisture retention characteristics for the tuff host rock (represented by sample S-19 from well USW GU-3) and backfill materials (represented by sand and clay) are illustrated in Fig. 2. The associated unsaturated permeabilities are illustrated in Fig. 3. Moisture retention characteristics and unsaturated permeabilities for a different material used to simulate the host rock (sample G4-6 from well USW G-4) are also included in Figs. 2 and 3.

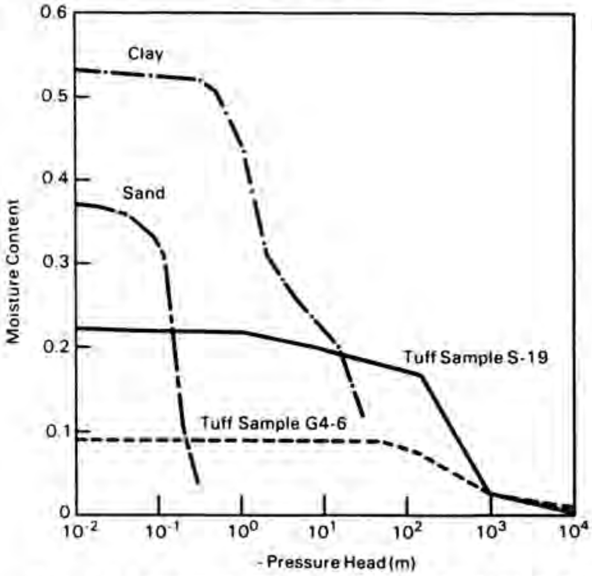


Fig. 2. Moisture retention characteristics for materials used to simulate the host-rock formation and backfill materials

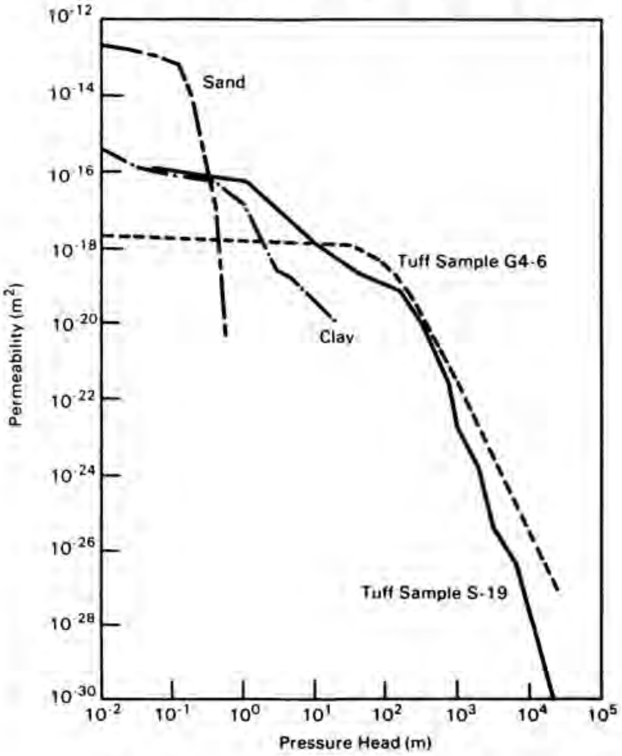


Fig. 3. Unsaturated permeability of materials used to simulate the host-rock formation and backfill materials

The calculations investigating backfilling the repository drift were largely *performed using* sample S-19 (from Gee 1982) to represent the host rock. The cases of sand and clay as backfill in the drift with sample G4-6 as the host rock were included when

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

additional hydraulic testing was completed.[13] The porosity and permeability of sample G4-6 are lower than for sample S-19 and are more representative of the prospective host rock, the densely welded portion of the Topopah Spring member of the Paintbrush tuff. This unit was selected[16] as the most suitable geologic unit in which to construct a nuclear waste repository in Yucca Mountain. Further, sample G4-6 is a densely welded tuff from the Topopah Spring member, whereas sample S-19 is a moderately welded tuff and is from a different geologic unit. The flux for cases using sample G4-6 was 0.01 cm/yr, which results in approximately 96 percent saturation of the host rock. Results from simulations with sample G4-6 as the host rock were used to confirm results from using sample S-19.

A simple analysis for determining proper grid spacing was applied (using sample S-19), by modeling a square region with progressively finer integrated finite difference cells until the solution did not change at steady state. Results of the grid-spacing analysis indicated that a maximum side dimension for the cells between 1.5 and 2.5 m was satisfactory.

Results with Sample S-19 Representing the Host Rock

The results comparing the repository drift with sand and clay backfill and sample S-19 as the host rock are illustrated in Figs. 4 through 7. Figs. 4 and 5 illustrate the distributions of

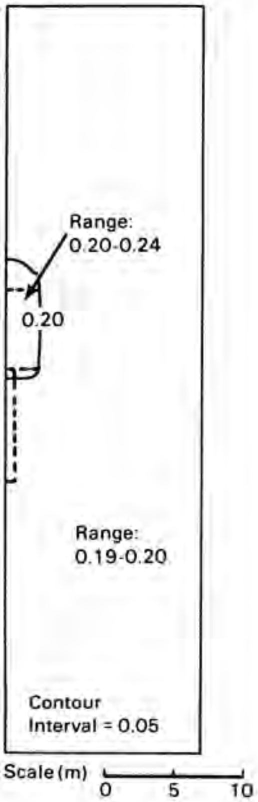

Fig. 4. Distribution of moisture content at steady state with clay backfill in the drift and sample S-19 as the host rock.

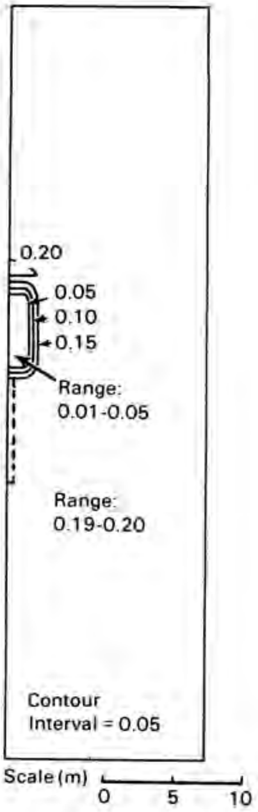

Fig. 5. Distribution of moisture content at steady state with sand backfill in the drift and sample S-19 as the host rock.

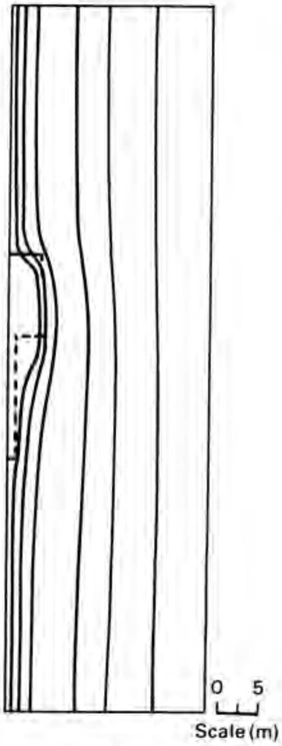

Fig. 6. Pathlines at steady state with clay backfill in the drift and sample S-19 as the host rock.

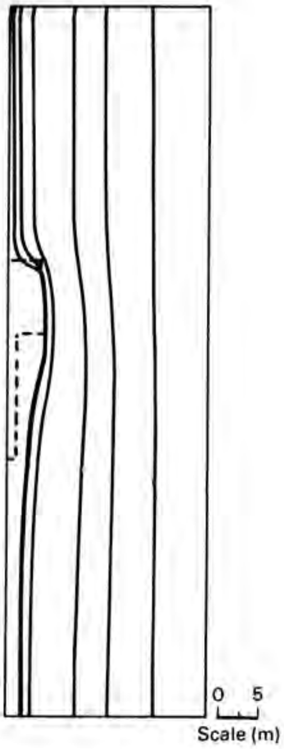

Fig. 7. Pathlines at steady state with sand backfill in the drift and sample S-19 as the host rock.

moisture content at steady state for the repository drift with clay and sand backfill, respectively. Figs. 6 and 7 are the pathlines at steady state for both clay and sand backfill, respectively.

We made the assumption that a range of hydrologic responses of the host rock formation could be obtained by (1) increasing and decreasing the saturated permeability of sample S-19 by two orders of magnitude and one order of magnitude, respectively, and (2) shifting the tuff sample S-19 in Fig. 3 up and down, without changing the shape of the curve. Results comparing the repository drift in host rock with permeability decreased by an order of magnitude are illustrated in Figs. 8 and 9. Fig. 8 illustrates the steady-state distribution of moisture content and Fig. 9 illustrates the pathlines for the case with host rock permeability decreased by an order of magnitude. The distribution of moisture content and pathlines for the case with host rock permeability increased by an order of magnitude are the same as those illustrated in Figs. 4 and 6, respectively.

Flow rates past the vertical waste package in cases investigated for the repository drift are listed in Table I. The flow rates are through an element of width 0.5 m adjacent to the waste package. A summary of water flow into the repository drift along with permeabilities inside the drift are provided in Table II.

The results demonstrate the difference between using coarse and fine materials for backfill in the repository drift in cases where sample S-19 was used to represent the host rock. Figs. 4 and 5 illustrate that sand drained more

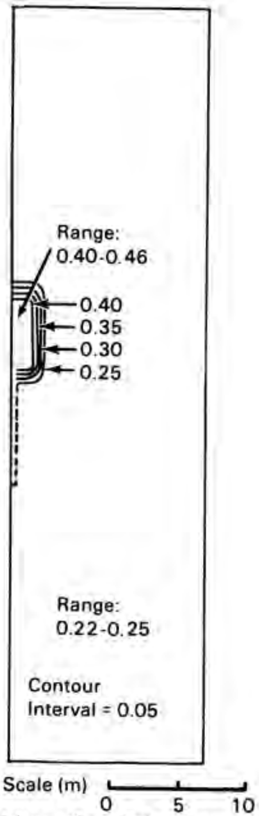

Fig. 8. Distribution of moisture content at steady state with clay backfill and decreased host-rock permeability (for sample S-19).

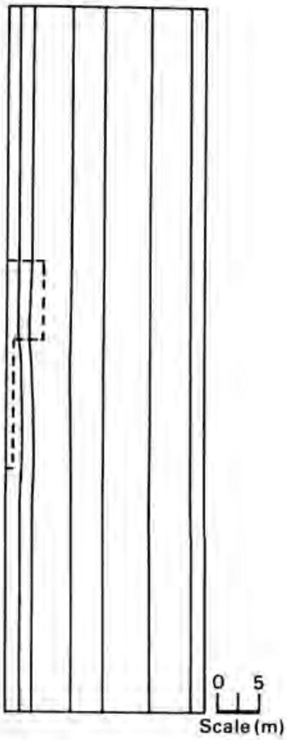

Fig. 9. Pathlines at steady state with clay backfill and decreased host-rock permeability (for sample S-19).

completely, indicated by the low moisture contents in the drift in Fig. 5, while clay retained moisture (Fig. 4). Further, the saturation state of the host rock was approximately 89 percent for both cases. An indication of the capillary barrier concept is the extremely low permeability ($9 \times 10^{-33}\ \text{m}^2$) of the sand backfill in the drift.

TABLE I

Steady-State Flow Rates Through an Element of Width 0.5 m and Length 1.5 m Adjacent to the Center of the Waste Package (see footnote (a) in Table II)

Fluid Flow in the Vertical Direction Past the Case	Waste Package (m^3/day)
Sample S-19, Clay Backfill	3.7×10^{-6}(a) 4.2×10^{-6}(b)
Sample S-19, Sand Backfill	3.6×10^{-6}(a) 4.1×10^{-6}(b)
Sample S-19 with Increased Permeability, Clay Backfill	4.8×10^{-6}(a) 5.2×10^{-6}(b)
Sample S-19 with Decreased Permeability, Clay Backfill	6.6×10^{-6}(a) 6.5×10^{-6}(b)
Sample G4-6, Clay Backfill	1.3×10^{-7}(a) 1.4×10^{-7}(b)
Sample G4-6, Sand Backfill	1.2×10^{-7}(a) 1.3×10^{-7}(b)

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

The drift with sand backfill (Fig. 7) distorted pathlines farther away from the waste package than the drift with clay backfill (Fig. 6). However, the vertical flow past the waste package is essentially the same for the clay- and sand-backfilled drifts (see Table I).

Increasing permeability by two orders of magnitude for the host rock produced little effect on flow through the repository drift. However, decreasing the host-rock permeability by an order of magnitude caused the drift to remain at a much higher moisture content (see Fig. 8). At higher saturation (98-99 percent) in the host rock with decreased permeability, water flow past the waste package increased an average of 66 percent (average of fluid flow into and out of the element listed in Table I); water flow into the repository drift increased by less than two orders of magnitude (see Table II) but was still extremely small. When the host rock permeability is decreased, there is some diversion of water from the host rock into the drift. As shown in Table II, the flow into the drift is 16.6 percent of the influx into the modeled area. If no drift were present, the amount of water passing through the area occupied by the drift would be 15 percent of the influx.

Results with Sample G4-6 Representing the Host Rock

Results for the two additional cases using sample G4-6 to represent the host rock show the same trend as the cases with sample S-19 representing the host rock. For the lower flux and decreased host-rock permeability, the clay backfill retained moisture (Fig. 10) while the sand backfill drained (Fig. 11). Permeability inside the drift is three orders of magnitude lower in the sand backfill compared to the clay (Table II), indicating that the sand will allow less moisture to enter the drift. Fluid flow into the drift was also slightly lower for the case with sand backfill in the drift (Table II). Illustrations of the pathlines at steady state for both sand and clay backfill are not included because they are identical to Fig. 6.

TABLE II

Summary of Water Flow Into and Permeability Inside the Repository Drift at Steady-State Conditions

Case	Fluid Flow into the Drift as a Percent of Influx(a)	Backfill Permeability m^2
Sample S-19, Clay Backfill	0.55(b)	1.1×10^{-19}
Sample S-19, Sand Backfill	0.0(b)	8.8×10^{-33}
Sample S-19 with Increased Permeability, Clay Backfill	0.26(b)	8.0×10^{-21}
Sample S-19 with Decreased Permeability, Clay Backfill	16.56(b)	1.0×10^{-17}
Sample G4-6, Clay Backfill	1.30(c)	7.7×10^{-21}
Sample G4-6, Sand Backfill	0.01(c)	1.0×10^{-24}

(a) Influx is the product of flux (either 0.4 cm/yr or 0.01 cm/yr), width (15.25 m), and depth of the modeled region (1 m).
(b) Influx = $1.671 \times 10^{-4}\ \text{m}^3$/day.
(c) Influx = $4.178 \times 10^{-6}\ \text{m}^3$/day.

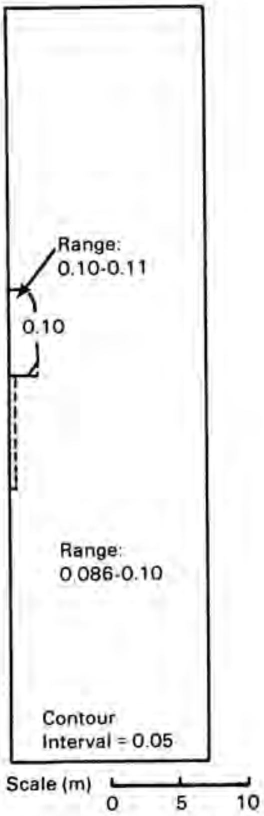

Fig. 10. Distribution of moisture content at steady state for sample G4-6 as the host rock and clay backfill in the drift.

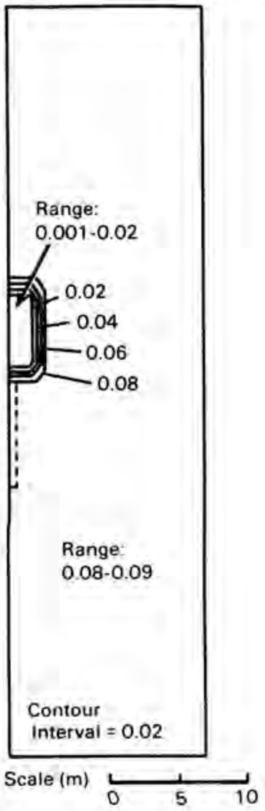

Fig. 11. Distribution of moisture content at steady state for sample G4-6 as the host rock and sand backfill in the drift.

CONCLUSIONS

The numerical analyses considered the effectiveness of backfill materials as barriers to water flow in a simple repository configuration. Based on results of the preliminary calculations, which assume flow through the rock matrix, 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 is not essential because backfill material cannot significantly influence flow around waste packages (see Tables I and II). However, backfill may be desired for structural or other reasons.[17]

- If backfilling the repository is desired, results of numerical simulations (see Table II) indicate that coarse materials perform more satisfactorily as barriers to water flow through drifts than fine materials in the unsaturated zone.

- More water flows into the repository drift (see Table II) when the surrounding host-rock formation is at high saturation (i.e., 98-99 percent).

- Using a different material to simulate the host rock (sample G4-6) does not alter the conclusions.

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