NOTICE

THIS REPORT IS ILLEGIBLE TO A DEGREE
THAT PRECLUDES SATISFACTORY REPRODUCTION

LBL-17490

CONF-850101--3

Lawrence Berkeley Laboratory

UNIVERSITY OF CALIFORNIA

DR-0827-3

EARTH SCIENCES DIVISION

To be presented at the International Association of Hydrogeologists 17th International Congress, Tucson, AZ, January 7-10, 1985

MODELING OF STRONGLY HEAT-DRIVEN FLOW IN PARTIALLY SATURATED FRACTURED POROUS MEDIA

LBL--17490

DE85 004660

K. Pruess, Y.W. Tsang, and J.S.Y. Wang

October 1984

Prepared for the U.S. Department of Energy under Contract DE-AC03-76SF00098

LEGAL NOTICE

MODELING OF STRONGLY HEAT-DRIVEN FLOW IN PARTIALLY SATURATED FRACTURED POROUS MEDIA

K. Pruess, Y. W. Tsang, and J. S. Y. Wang
Earth Sciences Division, Lawrence Berkeley Laboratory
University of California, Berkeley, California 94720

Abstract

We have performed modeling studies on the simultaneous transport of heat, liquid water, vapor, and air in partially saturated fractured porous media, with particular emphasis on strongly heat-driven flow. The presence of fractures makes the transport problem very complex, both in terms of flow geometry and physics. The numerical simulator used for our flow calculations takes into account most of the physical effects which are important in multi-phase fluid and heat flow. It has provisions to handle the extreme non-linearities which arise in phase transitions, component disappearances, and capillary discontinuities at fracture faces. We model a region around an infinite linear string of nuclear waste canisters, taking into account both the discrete fractures and the porous matrix. From an analysis of the results obtained with explicit fractures, we develop "equivalent" continuum models which can reproduce the temperature, saturation, and pressure variation, and gas and liquid flow rates of the discrete fracture-porous matrix calculations. The "equivalent" continuum approach makes use of a generalized relative permeability concept to take into account the fracture effects. This results in a substantial simplification of the flow problem which makes larger scale modeling of complicated unsaturated fractured porous systems feasible. Potential applications for regional scale simulations and limitations of the continuum approach are discussed.

INTRODUCTION

Modeling fluid flow and heat transfer in fractured porous media is important for the assessment of nuclear waste repository impacts. Most of the potential repository sites currently being studied in the U.S. are in saturated formations below the water table. The tuff formations at the Nevada Test Site are unique in that the potential repository horizon is located above the water table in partially saturated rock. The very thick (up to 600 m) unsaturated zone offers a number of advantages for waste disposal in comparison to saturated rock of low permeability, including (1) the probable absence of an effective mechanism to dissolve and transport the radionuclides to a deep water table under present arid climatic conditions, (2) protection from erosion, (3) availability of remote federally owned lands, and (4) relative ease of placement and retrieval (Winograd, 1974).

The tuffs have both matrix and fracture porosity and permeability. At the potential repository horizon, 300 m below the ground surface, approximately 80% of the pore volume contains water, which is held in the porous matrix by capillary suction. The remaining voids contain air and a small amount of water vapor at ambient pressures and temperatures (p = 1 bar, T = 26°C). To evaluate the suitability of the unsaturated zone as a disposal medium for high-level nuclear waste, one must consider the effects of a strong heat source upon liquid and gas movement in the unsaturated zone. We have applied a recently developed multi-phase multi-component code, TOUGH (Pruess, 1984), to model the effects of heat on the flow through discrete fractures and porous matrix around the waste. Based on understanding and insight gained from the discrete fracture-porous matrix simulations, we develop "equivalent" single continuum models to obtain a simplified description of the thermo-hydrologic response of a partially saturated fractured porous medium to nuclear waste emplacement.

MULTI-PHASE APPROACH TO NON-ISOTHERMAL UNSATURATED FLOW

The "conventional" description of unsaturated flow, as recently reviewed by Narasimhan (1982), was developed primarily by soil physicists. It assumes isothermal conditions and treats the gas phase as a passive spectator, which remains at constant pressure (1 bar) at all times. Liquid phase flows under gravity and capillary suction, as given by Richards' law (1931). This approach has been extended to "weakly" non-isothermal systems (temperatures up to 50°C) by Philip and de Vries (1957), Sophocleous (1979), Milly (1982), and others. These authors include effects of water vapor transport by molecular diffusion, but no overall movement of the gas phase is taken into account. The present status of "weakly" non-isothermal unsaturated flow has been reviewed by Walker, Sabey, and Hampton (1981), and Childs and Malstaff (1982).

Emplacement of high-level nuclear waste in partially saturated rock presents a "strongly" heat-driven problem, for which the approaches mentioned above are not applicable. Near the waste packages absolute temperatures may almost double (from ambient 300 K to near 600 K). From the ideal gas law $pV = nRT$ one then expects large increases in pressure and/or volume of the gas phase, which will give rise to strong forced convection of the gas phase from thermal expansion. Even stronger gas phase flow effects are expected from vaporization of liquid water, which will become vigorous when formation temperatures exceed 100°C. To describe these phenomena it is necessary to employ a multi-phase approach to fluid and heat flow, which fully accounts for the movement of gaseous and liquid phases, their transport of latent and sensible heat, and phase transitions between liquid and vapor. The gas phase will in general consist of a mixture of water vapor and air, and both these components must be kept track of separately.

We have developed a numerical simulator called "TOUGH" (transport of unsaturated groundwater and heat), which can represent most of the physical processes of significance in two-phase flow of water and air with simultaneous heat transport (Pruess, 1984). The formulation used in TOUGH is analogous to the multi-phase treatment customarily employed in geothermal reservoir simulators (Pruess, 1983; O'Sullivan et al., 1983). Similar numerical models have been recently developed, or are being developed, by other authors (Travis, 1983; Eaton et al., 1983; Hadley, private communication, 1984; Bixler, 1984). Table 1 summarizes the physical effects which impact on fluid and heat transport. Check marks indicate processes or effects which are presently accounted for in the governing equations solved by the TOUGH simulator. Processes which are checked off in parentheses are at present implemented in an approximate way. Other effects currently not accounted for in the computer model may be significant, and are being studied. TOUGH solves the heat and mass balance equations for the components air and water. These equations are strongly coupled and are highly non-linear, because of order-of-magnitude changes in parameters during phase transitions, and because of non-linear material properties (chiefly relative permeability for gas and liquid phases and capillary pressures). Because of these features of the equation system, TOUGH performs a completely simultaneous solution of the discretized mass- and energy-balance equations, taking all coupling terms into account. Space discretization is made with the integral finite difference method (IFD; Narasimhan and Witherspoon, 1976). Time is discretized fully implicitly as a first-order finite difference, to obtain the numerical stability needed for an efficient calculation of flow in fractures with extremely small volumes. Newton-Raphson iteration is performed to handle the nonlinearities. The linear equations arising at each iteration step are solved directly, using Gaussian elimination and sparse storage techniques (Duff, 1977). The numerical performance of TOUGH was verified by comparison with a number of geothermal reservoir and unsaturated flow problems, for which analytical or numerical solutions are available (Pruess and Wang, 1984).

Table 1: Physical Processes in Strongly Heat-Driven Flow in Partially Saturated Rocks

1. Fluid Flow		2. Heat Flow
✓ pressure forces		✓ conduction
✓ viscous forces		✓ flow of latent and sensible heat
inertial forces		radiation
✓ gravity		3. Vaporization and Condensation
✓ interference between liquid and gas		✓ temperature and pressure effects
✓ dissolution of air in liquid		✓ capillarity and adsorption
✓ capillarity and adsorption	liquid	4. Changes in Rock Mass
differential heat of wetting	liquid	(✓) thermal expansion
chemical potential gradients	liquid	(✓) compression under stress
✓ mixing of vapor and air	gas	thermal stress cracking
✓ vapor pressure lowering	gas	(✓) change in porosity and
✓ binary diffusion	gas	permeability
Knudsen diffusion	gas	
thermodiffusion	gas	

DISCRETE AND CONTINUUM MODELS FOR FLOW IN FRACTURED ROCKS

A substantial complication of the flow problem considered here arises from the complex geometric characteristics of fractured rock with significant matrix porosity and permeability. Numerical modeling of fluid and heat flow in fractured media can be approached in several different ways. Conceptually it is most straightforward to model the discrete fractures explicitly, using small volume elements, together with porous matrix blocks. The explicit discretization approach to modeling flow in fractured media is suitable for fundamental studies of idealized systems, but it is not practical for most "real" problems, where the amount of geometric detail and complexity is far beyond the capacity of digital computers, and where available field data on fracture distributions are typically rather incomplete. Moreover, in modeling thermohydrological conditions one is usually interested in predicting averages over some macroscopic scale, and too much detail on the level of individual fractures would be useless.

A powerful approach to modeling of flow in fractured media is the *double-porosity method*, originally developed by Russian hydrologists (Barenblatt et al., 1960), and introduced into the petroleum literature by Warren and Root (1963). In this method, the "primary" porosity in the rock matrix and the "secondary" porosity in the fractures are each treated as a continuum. The global flow in the medium occurs only through the *fracture continuum*, while matrix and fractures interact locally by means of "interporosity" flow. The classical double-porosity method employed a quasi-steady approximation for interporosity flow. This was extended to a method of multiple interacting continua (MINC) by Pruess and Narasimhan (1982a, b) for problems with highly transient interporosity flow of multi-phase fluids and heat. In many cases the double-and multiple-porosity methods still require a very large amount of computational work, so that it would be desirable to go one step further and attempt to approximate the fluid and heat flow in a fractured medium by means of a single effective or "equivalent" continuum. Possibilities and limitations for representing the permeability of a fracture system by means of an equivalent porous medium have been studied by Long et al. (1982). These authors have considered steady isothermal single-phase flow in fracture networks, with completely impermeable matrix.
In our case, extensive boiling of formation water occurs mainly in the matrix, so that matrix permeability and porosity cannot be ignored. The problem of developing an "equivalent" continuum description for multi-phase flow in a fractured porous medium is considerably more difficult than the problem of

single-phase, fracture-only flow. It can be shown that at least two continua are required to avoid basic inconsistencies in the representation of fractured porous flow (Pruess et al., 1984). However, because of the computational complexities of even the simplest two-continuus model, we believe it worthwhile nonetheless to attempt to develop single continuum models which can adequately predict certain aspects of the thermohydrological response to waste emplacement. In the present study, we develop single "equivalent" continuum models which yield approximately the same temperature, pressure, and saturation distributions and mass fluxes as an explicit discrete fracture-porous matrix model, given the same initial and boundary conditions.

OUTLINE OF MODELING APPROACH

As a first step, we perform detailed modeling studies of fluid and heat flow near waste packages emplaced in fractured porous tuff, using an explicit representation of fractures. To accomplish such modeling it is necessary to idealize fracture and waste emplacement geometry. Specifically, we consider only one set of plane, parallel, infinite fractures, which intersects an infinite linear string of waste packages at a right angle (Figure 1). Apart from this idealization we do employ geometric and matrix hydrologic parameters which, although preliminary, have been suggested as representative of actual values for the system under study. However, hydrologic properties of the fractures are rather poorly known at present. Therefore, hypothetical cases are studied to explore possible system behavior.

These explicit fracture studies provide a detailed "microscopic" look at system evolution after waste emplacement. The results obtained, while of interest in their own right, then serve as "benchmarks" in a second step, where we generate fluid and heat flow predictions for various single-continuum models in search for an "equivalent" continuum. Specifically, based on the process characteristics observed in the explicit fracture models, we propose single-continuum parameters which might be expected to yield a behavior similar to the explicit fracture model. The continuum models are tested by comparing predictions for temperatures, pressures, saturation profiles, and mass and heat flow rates with those obtained in the explicit fracture models. In this way it is possible to evaluate utility and validity of the continuum models.

SPECIFICATION OF THE EXPLICIT DISCRETE FRACTURE-POROUS MATRIX STUDIES

In the calculations reported here we neglect gravity and infiltration effects. For the idealized geometry shown in Figure 1, it is then only necessary to model a symmetry element, as indicated by dashed lines. However, for convenience we will quote results for extensive quantities such as fluid and heat flow rates, on a "per waste package" basis. The calculations for the discrete fracture-porous matrix studies were carried out using a two-dimensional r-z grid. Discretization in the r direction consists of 44 concentric cylinders which extend from the canister wall to r = 300 m; the radial spacing of the cylinders increases non-uniformly with r. In z direction we discretize into four layers having thicknesses (in 10^{-3} m) of 1, 4, 15 and 90 respectively. The first layer represents (half of) the fracture. Most of the formation parameters (Keith Johnstone, private communication, 1983) used in the calculations are summarized in Table 2. Characteristic curves (relative permeability and suction pressure) are only given for the rock matrix. The characteristic curves for the fractures are not known experimentally. To arrive at the characteristic curves for the fractures in our calculations, we proceed as follows.

Upon close examination of the measured suction curve for the tuff matrix as shown in Figure 2, we note that the very strong suction pressures such as -2000 bars at low liquid saturation in the matrix ($S_{\ell,m}$ = 2%) cannot represent effects of capillary pressure related to the curvature of the matrix pores. (Indeed, the capillary radius corresponding to $P_{suction}$ = -2000 bars is 7.3×10^{-8} cm, or

Table 2: Formation Parameters

Matrix	
rock grain density	$\rho_R = 2550\ kg/m^3$
rock specific heat	$C_R = 768.8\ J/kg\,^\circ C$
rock heat conductivity (dry)	$K = 1.6\ W/m\,^\circ C$
porosity	$\phi_m = 10.3\ \%$
permeability	$k_m = 32.6 \times 10^{-18}\ m^2$
suction pressure	$P_{suc}(S_\ell) = -1.393\ (S_{EF}^{-1/\lambda}-1)^{1-\lambda}$ MPa
relative permeability to liquid (van Genuchten, 1980)	$k_{r\ell}(S_\ell) = \sqrt{S_{EF}}\ [1-(1-S_{EF}^{1/\lambda})^\lambda]^2$
relative permeability to gas	$k_{rg}(S_\ell) = 1 - k_{r\ell}$
	where $S_{EF} = (S_\ell - S_{\ell r})/(1 - S_{\ell r})$, $S_{\ell r} = 9.6 \times 10^{-4}$, $\lambda = 0.45$
Fractures (one vertical set)	
aperture	$\delta = 2$ mm
porosity	$\phi_f = 20\ \%$
spacing	$D = .22$ m
average continuum permeability	$\bar{k}_f = 10^{-13}\ m^2$
permeability per fracture*	$k_f = \bar{k}_f \cdot D/\delta = 11 \times 10^{-12}\ m^2$
equivalent continuum porosity	$\bar{\phi}_f = \phi_f \delta / D = 0.182\ \%$
Initial Conditions	
temperature	$T = 26\ ^\circ C$
pressure	$p = 10^5$ Pa ($\equiv$ 1 bar)
liquid saturation in matrix	$S_{\ell,m} = 80\ \%$

*Note that we do not imply a parallel-plate model for the fractures; k_f is less than the parallel plate permeability $(\phi_f \delta)^2/12 = 1.33 \times 10^{-8}\ m^2$.

approximately twice the diameter of a water molecule!). In this range of low liquid saturation the suction curve in fact represents the effects of liquid phase adsorption on the solid surface of the rock. The transition from capillary mechanism to adsorption mechanism has been studied in concrete slabs (Huang et al., 1979). Since the adsorption mechanism depends only on the physical-chemical properties of the rock-liquid interaction, but not on the curvature of the pore surfaces, we expect that the same effects are present on the fracture surfaces as on the matrix pore surfaces at low liquid saturations. At the ambient suction $P_{suc} = -10.93$ bar for the matrix at initial liquid saturation $S_{\ell,m} = 80\%$, the liquid cannot be held by capillary force in the fractures. If we apply the expression, $P_{cf} = -2\sigma/\delta$, to the fracture, where σ is the surface tension and δ is the fracture aperture, we obtain at ambient temperature $P_{cf} = -.00073$ bar, which is much smaller than the ambient suction $P_{suc} = -10.93$ bar. Therefore, liquid can be present on the fracture surfaces only as a thin film of a few molecular layers. We propose that the very strong suction at low liquid saturation for the matrix shown in Figure 2 is also encountered over a small interval of low liquid saturations in the fractures. The thin film of liquid on the fracture walls presumably has extremely low mobility. Specifically, we assume an immobile saturation $S_{\ell r}$ such that liquid relative permeability in the fracture $k_{r\ell}\ (S_\ell) = 0$ for $S_\ell \leq S_{\ell r}$. For $S_\ell > S_{\ell r}$, the liquid and gas fracture relative permeabilities are assumed to be linear functions of saturation and to obey the relationship $k_{r\ell} + k_{rg} = 1$ as suggested in the geothermal literature (Pruess et al., 1983).

In this study, we model two cases which are intended to illustrate alternative possible system behavior. These cases differ with respect to mobility of liquid in the fracture at the initial (pre-emplacement) liquid saturation. We choose $S_{\ell r} = 1\%$ for the liquid permeability cut off in the fractures. Then we assume a linear variation of suction pressure with liquid saturation over the range of $0 \le S_\ell \le 1\%$ in the first case and over the range of $0 \le S_\ell \le 5\%$ in the second case. Before canister emplacement, matrix and fractures will be in capillary equilibrium. The above choice of parameters gives the initial liquid saturation in the fracture $S_{\ell,f} = .9878\%$ in Case 1 and $S_{\ell,f} = 3.928\%$ in Case 2. Hence the liquid is initially immobile in Case 1 and has a relative permeability of $k_{r\ell,f} = 2.96\times10^{-2}$ in Case 2.

RESULTS OF DISCRETE FRACTURE-POROUS MATRIX STUDIES

Calculated results for Case 1 are given in Figures 4 through 8, and for Case 2 in Figures 9 through 13. For comparison we have also included results for porous medium models with no allowance for fractures, as well as for "equivalent" continuum models, to be described in the next section. We shall first describe the simulated response of the porous fractured system to waste package emplacement in a general way as shown schematically in Figure 3. Detailed discussion of the computed results will be given in conjunction with introduction of equivalent continuum concepts and parameters below.

Emplacement of waste packages causes temperatures to rise in both rock matrix and fractures. Initially this causes evaporation of a modest amount of liquid water, as the partial pressure of vapor increases according to the saturation curve $P_v = P_{sat}(T)$. Boiling becomes vigorous as the temperature reaches 100°C. Most of the vapor generated in the rock matrix flows towards the fractures, and then flows radially outward in the fractures, where it soon condenses on the cooler walls of the rock. In Case 1, where liquid is initially immobile in the fractures, the condensed liquid re-enters the matrix under capillary suction, and then migrates down the saturation profile towards the boiling region near the waste package. However, because of low matrix permeability, radial outflow of vapor in the fractures exceeds radial inflow of liquid in the matrix, so that the rock near the waste package becomes desaturated (dries up). As time progresses the entire spatial pattern of vaporization in the matrix, vapor discharge into the fractures, condensation at fracture walls and liquid backflow in the matrix towards the heat source slowly migrates radially outward, away from the canister. Even though liquid is only barely immobile in the fractures initially, it remains immobile at all times. The very slight saturation buildup of $\Delta S_\ell > 0.0122\%$ required to achieve liquid mobility in the fractures is never accomplished, because capillary suction in the matrix is sufficiently strong to draw liquid out of the fractures at the same rate as it condenses.

The behavior of the condensed liquid is entirely different in the second case, where liquid has a finite mobility in the fractures. The slight saturation increase in the fractures as a consequence of condensation induces a suction gradient and associated liquid flux in the fracture. The extremely large fracture permeability gives rise to rapid movement of water away from the condensation front, both radially inward and outward. In this way the condensed water is rapidly distributed over the fracture faces, with little water entering the matrix near the condensation front. Backflow of liquid towards the boiling region near the canister is facilitated by the high-permeability pathway in the fractures. With time a balanced vapor-liquid counterflow is established, which stabilizes the saturation profile near the canister, and prevents the drying process from going very far. This suction-driven two-phase counterflow represents an extremely efficient heat transfer mechanism known as "heat pipe" (Eastman, 1968). In the present case, the "overpressure" needed to drive the heat pipe is small because of the large fracture permeability. Gas phase pressures always remain close to 1 bar, so that temperatures in the fractures remain at or below 100 °C. Because of the small fracture spacing the pathways for vapor flow and heat conduction from the rock matrix to the fractures are short (< 11cm), and temperature and pressure conditions remain close to (T, P) = (100 °C, 1 bar) even in the rock matrix. This is in contrast to Case 1 where the temperature rises to much higher values.

EQUIVALENT CONTINUUM MODELS

We shall now examine in detail the simulated fluid and heat flow processes in a fractured porous medium in an attempt to identify the *specific effects of fractures*, and to approximate these effects by means of a single continuum with suitably chosen "effective" hydrologic parameters. For Case 1 with liquid immobile in the fractures at all times, it appears that the *role of the fractures* is solely to provide a high-permeability pathway for gas phase flow, while having no effects on liquid flow. This suggests a very simple prescription for effective continuum parameters which should be able to represent these effects. Namely, we prescribe a very large relative permeability k_{rg} = 3067 for the gas phase, so that effective gas permeability $k_{rg} \cdot k_m = 10^{-13}$ m^2 is equal to the average continuum permeability $\bar{k}_f$ of the fractures, independent of saturation. We make no changes whatsoever in the other rock matrix parameters. Calculated results from this model are labeled "porous matrix with large effective gas permeability" in Figures 4 through 8. Comparison with the detailed fracture calculation, and with porous medium calculations without fractures, reveals the following trends.

There is excellent agreement between the calculation using explicit fractures and the "equivalent" continuum with large gas permeability in all important parameters, i.e., temperatures, pressures, liquid saturation, and gas and liquid flow rates. In each figure, the intensive quantities, temperature, pressure and saturation, from the explicit discrete fracture-porous matrix calculations are averaged over the pore volumes of the grid layers at each radius and the extensive flow rates are summed over the grid layers for meaningful comparison with continuum models. The results obtained from the "no fractures" calculation (unmodified rock matrix parameters) are generally rather different. Saturation and pressure profiles, as well as flow rates of gas and liquid, show rather dramatic fracture effects which are very well reproduced by the "equivalent" continuum model with large gas permeability. Temperatures are not very strongly affected by the presence of fractures in this case with immobile water in the fractures, because of absence of sufficient permeability for water flow.

For Case 2 with liquid mobile in the fractures, the role of the fractures is to provide high-permeability pathways for both the liquid flow and the gas flow, while the matrix acts as the fluid source. To take into account the fracture effects, we modify two parameters: the relative permeability for the liquid flow and the relative permeability for the gas flow. We assign for the liquid flow the relative permeability $k_{r\ell}$ = 90.65, so that the effective liquid permeability $k_{r\ell} \cdot k_m = (k_{r\ell,f}) \cdot (\bar{k}_f)$ = 2.96×10^{-15} m^2, where $k_{r\ell,f} = 2.96 \times 10^{-2}$ is the relative permeability for liquid flow along discrete fractures at initial saturation, and $\bar{k}_f$ is the average continuum permeability of the fractures. We also assign for the gas flow a large relative permeability k_{rg} = 2976.35 so that $k_{rg}\ k_m$ = $(k_{rg,f})\ (\bar{k}_f)$. As in Case 1, all other formation parameters are the *same as for the porous* medium model without fractures. Calculated results from the mobile liquid "equivalent" continuum model are labeled "porous continuum with large effective liquid and gas permeabilities" in Figures 9 through 13.

There is again excellent agreement between the calculation using explicit fractures and the "equivalent" continuum with large liquid and gas permeabilities for temperatures, liquid saturation in the matrix, gas and liquid flow rates, and pressures in the fractures. The discrete fracture calculations show that vapor condensation on the fracture walls never changes liquid saturation in the fractures by more than 1.2 x 10^{-3} %, indicating that the suction pressure gradient is sufficiently strong to rapidly distribute the liquid over the fracture surfaces. With nearly constant saturation, we can use the initial saturation to determine the constant relative permeability which is used for the "equivalent" continuum model. Near the canister with incensive boiling in the matrix, the pressure in the matrix is slightly higher than in the fractures, which is the driving mechanism for the gas flow from the matrix to the fractures (see Figure 11). This interporosity flow normal to the matrix-fracture interfaces is not accounted for in the "equivalent" continuum formulation. Away from the immediate vicinity of the waste canisters, the "equivalent" continuum model with large liquid and gas permeabilities faithfully reproduces the movements of gas and liquid. Figures 9 through 13 show that the results from the "no fractures" calculation are quite different from the models taking fractures into account. With liquid mobile in the fractures, the temperature near the waste canister will remain close to 100°C, and the thermally induced liquid flow can easily move away from the condensation front into the formation.

DISCUSSION

Our calculations show that in the presence of a strong heat source in a partially saturated fractured porous formation, gas (vapor/air) and liquid movements will be strongly influenced by the fractures. Our modeling studies indicate that the fracture effects can be represented in a single continuum by choosing appropriate gas and liquid relative permeabilities.

In modeling two alternate system behaviors (one with liquid immobile and the other with liquid mobile in the fractures), we show that if the liquid is initially mobile in the fractures the rock temperature will remain close to 100°C; while temperatures rise to much higher values when there is no liquid mobility in the fracture initially. This result suggests that stabilization of rock temperatures near 100°C is a characteristic signature of conditions where liquid is initially mobile in the fractures. With liquid mobile in the fractures, the thermally induced liquid movement occurs over a much larger region than in the case with no liquid mobility in the fractures.

In focusing on the interplay of pressure driving force and suction driving force in this study, we have neglected gravity effects. We are currently extending the equivalent continuum modeling studies, with inclusion of gravity, to examine the thermohydrological response to nuclear waste emplacement on a regional scale. For large scale modeling, it is neccessary to use "equivalent" continuum models as it is impractical to model all the discrete fractures together with the porous matrix. The results presented in this paper suggest that fracture effects on a regional scale can be adequately handled by means of equivalent continuum models.

It should be emphasized that the effective hydrologic parameters for an "equivalent" continuum depend not only on formation parameters, but also upon initial thermodynamic conditions, such as initial moisture content. Moreover, the effective continuum parameters will also depend upon the particular flow process considered, and upon the nature of the perturbation to which the fractured porous medium is subjected. The processes considered in this paper have the simple characteristic that liquid saturations in the fractures never change by more than a minute amount. It is this feature which makes possible a simple effective continuum representation in terms of (large) effective relative permeabilities. For other types of processes, such as major flood events with large saturation transients in the fractures, such simplifications are not applicable. In that case it may in fact not be possible to obtain an equivalent continuum description.

In conclusion, it should be emphasized that single continuum models can predict only certain aspects of the thermohydrologic response. We have demonstrated that "equivalent" continuum models can reproduce the temperature, pressure, saturation, and fluid flow fields generated from waste emplacement. However a single continuum gives only a single velocity field, which will either underestimate flow velocities in the fractures or overestimate flow velocities in the matrix. Furthermore, no description of interflow between fractures and matrix is made in the single continuum model. These deficiencies of the "equivalent" continuum approach may have a strong impact on predictions for transport of chemical species. Therefore, the utility of continuum models for predicting contaminant transport is uncertain at the present time.

ACKNOWLEDGEMENT

This work was supported, in part, by Sandia National Laboratories, and by the Director, Office of Energy Research, Office of Basic Energy Science, of the U. S. Department of Energy under Contract No. DE-AC03-76SF00098.

REFERENCES

Barenblatt, G. E. Zheltov, I. P., and Kochina, I. N., 1960, Basic Concepts in the Theory of Seepage of Homogeneous Liquids in Fissured Rocks, J. Appl Math. (USSR), Vol. 24, No. 5, pp. 1286-1303.

Bixler, N. E., 1984, NORIA - A Finite Element Computer Program for Analyzing Water/ Vapor/Air/Energy Transport in Porous Media, Sandia National Laboratories, SAND report in preparation, Albuquerque, NM.

Childs, S. W., and Malstaff, G., 1982, Final Report. Heat and Mass Transfer in Unsaturated Porous Media, Pacific Northwest Laboratory, Report PNL-4036, Richland, WA, February.

Duff, I. S., 1977, *MA28 - A Set of FORTRAN Subroutines for Sparse Unsymmetric Linear Equations*, AERE Harwell Report R 8730, July.

Eastman, G. Y., 1968, The Heat Pipe, Scientific American, Vol. 218, pp. 38-46.

Eaton, R. R., Gartling, D. K., and Larson, D. E., 1983, SAGUARO - A Finite Element Computer Program for Partially Saturated Porous Flow Problems, Sandia National Laboratories, Report SAND82-2772, Albuquerque, NM, June.

Huang, C. L. D., Siang, H. H., and Best, C. H., 1979, Heat and Moisture Transfer in Concrete Slabs, Int. J. Heat Mass Transfer, Vol. 22, pp. 257-266.

Long, J. C. S., Remer, J. S., Wilson, C. R., and Witherspoon, P. A., 1982, Porous Media Equivalents for Networks of Discontinuous Fractures, Water Resources Research, Vol. 18, No. 3, pp. 645-658.

Milly, P. C. D., 1982, Moisture and Heat Transport in Hysteretic, Inhomogeneous Porous Media: A Matric-Head Based Formulation and a Numerical Model, Water Resources Research, Vol. 18, No. 3, pp. 489-498.

Narasimhan, T. N., and Witherspoon, P. A., 1976, An Integrated Finite Difference Method for Analyzing Fluid Flow in Porous Media, Water Resources Research, Vol. 12, No. 1, pp. 57-66.

Narasimhan, T. N., 1982, Physics of Saturated-Unsaturated Subsurface Flow, in: T. N. Narasimhan (ed.), Recent Trends in Hydrogeology, The Geological Society of America, Special Paper 189.

O'Sullivan, M. J., Bodvarsson, G. S., *Pruess, K., and Blakeley*, M. R., 1983, Fluid and Heat Flow in Gas-Rich Geothermal Reservoirs, paper SPE-12102, presented at the Society of Petroleum Engineers 58th Annual Technical Conference and Exhibition, San Francisco, CA., October (to appear in Soc. Pet. Eng. J.).

Philip, J. R., and de Vries, D. A., 1957, Moisture Movement in Porous Materials under Temperature Gradients, EOS Trans. AGU, Vol. 38, No. 2, pp. 222-232.

Pruess, K., 1983, Heat Transfer in Fractured Geothermal Reservoirs with Boiling, Water Resources Research, Vol. 19, No. 1, pp. 201-208, February

Pruess, K., 1984, *TOUGH - A Numerical Model for Strongly Heat Driven Flow in Partially Saturated Media*, LBL Earth Sciences Division Annual Report, pp. 39-41, also paper in preparation.

Pruess, K., Bodvarsson, G. S., and Stefansson, V., 1983, Analysis of Production Data From the Krafla Geothermal Field, Iceland, paper presented at Ninth Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, CA.

Pruess, K., and Narasimhan, T. N., 1982, *On Fluid Reserves* and the Production of Superheated Steam from Fractured, Vapor-Dominated Geothermal Reservoirs, Journal of Geophysical Research, Vol. 87, No. B11, pp. 9329-9339.

Pruess, K., and Narasimhan, T. N., 1982, A Practical Method for Modeling Fluid and Heat Flow in Fractured Porous Media, Proceedings Sixth SPE-Symposium on Reservoir Simulation, paper SPE-10509, New Orleans, LA., February (to appear in Soc. Pet. Eng. J.).

Pruess, K., Tsang, Y. W., and Wang, J. S. Y., 1984, Modeling of Strongly Heat Driven Flow in Partially Saturated Fractured Porous Media, Lawrence Berkeley Laboratory Report, LBL-18552.

Pruess, K., and Wang, J. S. Y., 1984, TOUGH - A Numerical Model for Nonisothermal Unsaturated Flow to Study Waste Canister Heating Effects, in: G. L. McVay (ed.) , Mat. Res. Soc. Symp. Proc., Vol. 26, Scientific Basis for Nuclear Waste Management, p. 1031-1038, North Holland, New York.

Richards, L. A., 1931, Capillary Conduction of Liquids through Porous Mediums, Physics, Vol. 1, pp. 318-333.

Sophocleous, M., 1979, Analysis of Water and Heat Flow in Unsaturated-Saturated Porous Media, Water Resources Research, Vol. 15, No. 5, pp. 1195-1206.

Travis, B. J., 1983, WAFE: A Model for Two-Phase Multi-Component Mass and Heat Transport in Porous Media, draft report, Los Alamos National Laboratory.

van Genuchten, M. Th., 1980, A Closed-Form Equation for Predicting the Hydraulic Conductivity of the Unsaturated Soils, Soil Sci. Soc. Am. J., Vol. 44, pp. 892-898.

Walker, W. R., Sabey, J. D., and Hampton, D. R., 1981, Studies of Heat Transfer and Water Migration in Soils, Final Report, Department of Agricultural and Chemical Engineering, Colorado State University, Fort Collins, CO., 80523, April.

Warren, J. E., and Root, P. J., 1963, The Behavior of Naturally Fractured Reservoirs, Soc. of Pet. Eng. J., pp. 245-255, September.

Winograd, I. J., 1974, Radioactive Waste Storage in the Arid Zone, EOS, Transactions of the American Geophysical Union, Vol. 55, No. 10, pp. 884-894, October.

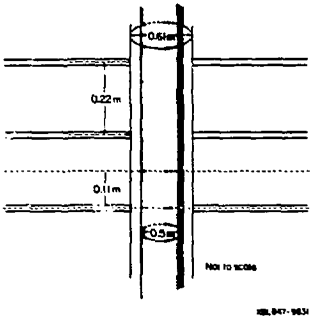

Fig. 1. Idealized emplacement configuration. An infinite linear string of waste packages is intersected by fractures with 0.22 m spacing.

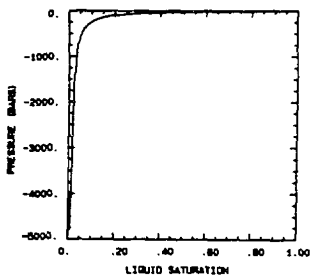

Fig. 2. Suction pressure of tuff matrix.

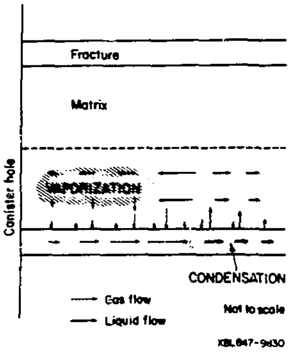

Fig. 3. Response of fractured porous medium to heat load for case with immobile liquid in fractures.

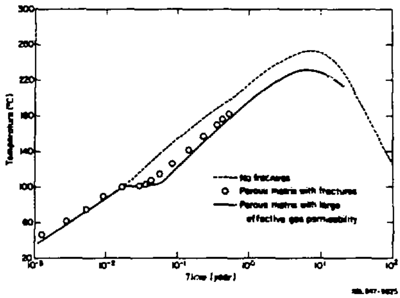

Fig. 4. Simulated temperatures at a distance of r = 0.3355 m from the canister centerline (Case 1; liquid immobile in fractures).

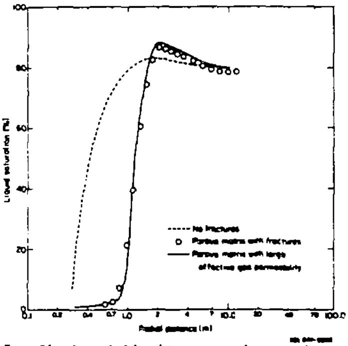

Fig. 5. Simulated liquid saturation profiles at t = 160 days (Case 1; for the fractured medium an average of fracture and matrix saturations is plotted).

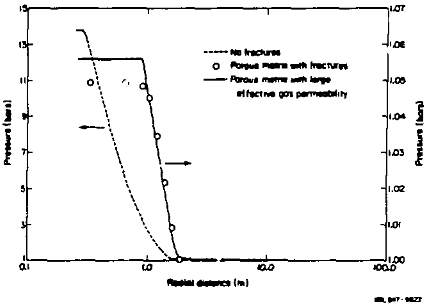

Fig. 6. Simulated pressure profiles at t = 160 days (Case 1; for the fractured medium the pressure in the fractures is plotted; note the different scales!).

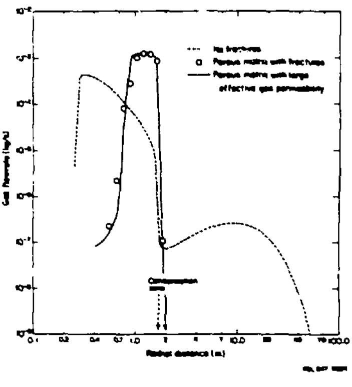

Fig. 7. Simulated rates of radial gas flow per waste package at t = 160 days (Case 1).

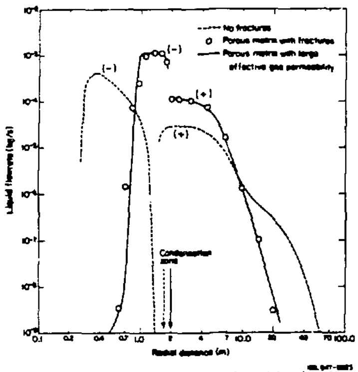

Fig. 8. Simulated rates of radial liquid flow per waste package at t = 160 days (Case 1; a "-" sign indicates flow towards the waste packages).

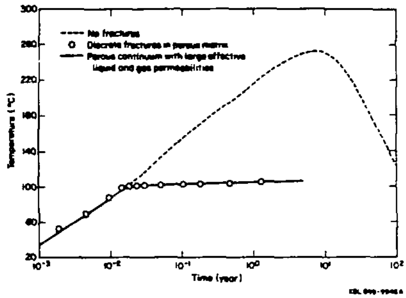

Fig. 9. Simulated temperatures at a distance of r = 0.3355 m from the canister centerline (Case 2; liquid mobile in fractures).

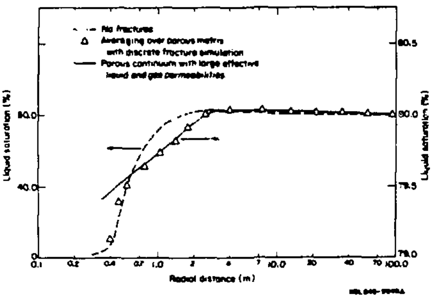

Fig. 10. Simulated liquid saturation profiles at t = 1 year (Case 2; note the different scales!).

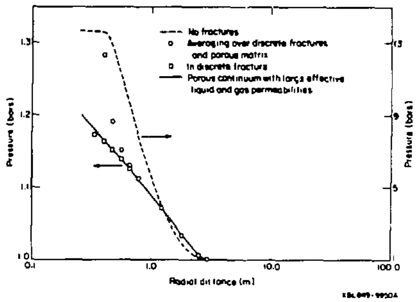

Fig. 11. Simulated pressure profiles at t = 1 year (Case 2; note the different scales!).

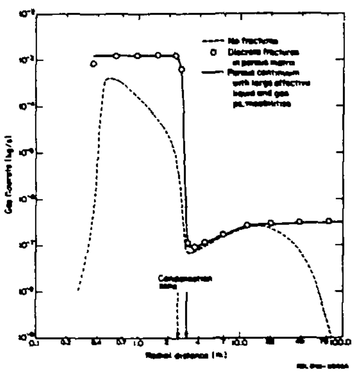

Fig. 12. Simulated rates of radial gas flow per waste package at t = 1 year (Case 2).

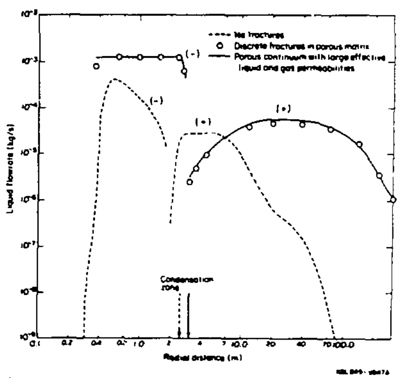

Fig. 13. Simulated rates of radial liquid flow per waste package at t = 1 year (Case 2, a "-" sign indicates flow towards the waste packages).