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Author

Pruess, K.

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Lawrence Berkeley Laboratory

UNIVERSITY OF CALIFORNIA

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K. Pruess

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DISCLAIMER

A QUANTITATIVE MODEL OF VAPOR DOMINATED GEOTHERMAL RESERVOIRS AS HEAT PIPES IN FRACTURED POROUS ROCK

Karsten Pruess

Earth Sciences Division, Lawrence Berkeley Laboratory
University of California, Berkeley, California 94720

ABSTRACT

We present a numerical model of vapor-dominated reservoirs which is based on the well-known conceptual model of White, Muffler, and Truesdell. Computer simulations show that upon heat recharge at the base a single phase liquid-dominated geothermal reservoir in fractured rock with low matrix permeability will evolve into a two-phase reservoir with B.P.D. (boiling point-for-depth) pressure and temperature profiles. A rather limited discharge event through cracks in the caprock, involving loss of only a few percent of fluids in place, is sufficient to set the system off to evolve a vapor-dominated state. The attributes of this state are discussed, and some features requiring further clarification are identified.

INTRODUCTION

Most geothermal reservoirs are of the "liquid-dominated" type, in which reservoir pressures tend to increase with depth according to a hydrostatic gradient. In hotter liquid-dominated systems (temperatures > 250°C) the temperatures often follow a boiling point-for-depth relationship (B.P.D.). Only a few "vapor-dominated" systems are known worldwide which in their unexploited state exhibit extremely small vertical gradients of temperatures and pressures (e.g., Larderello, Italy; The Geysers, California; Matsukawa, Japan; Kawah Kamojang, Indonesia). In these reservoirs, temperatures of 240 ± 5°C are encountered over a vertical thickness of several hundred and up to 2000 meters, while pre-exploitation pressures are within measurement error equal to the saturation pressures at prevailing temperatures. From these simple observations two important conclusions can be drawn (White et al., 1971; Truesdell and White, 1973): (1) for a vapor-dominated reservoir to be possible the system must be essentially sealed laterally, or else it would be flooded by neighboring ground waters with hydrostatic pressure profile; and (2) liquid water must be present throughout the system, or else one could not understand why pressures are constrained by the vapor pressure-temperature relationship for water.

A comprehensive conceptual model of vapor-dominated systems has been developed by White, Muffler, and Truesdell (1971), and Truesdell and White (1973). These authors explained one of the more puzzling aspects of vapor-dominated systems, namely, the presence of substantial upward heat flow in a system with very small vertical temperature gradient. The mechanism involved is known as "heat pipe" (Eastman, 1968): in the central zone of a vapor-dominated system both vapor and liquid are mobile; vapor flows upward, condenses at shallower depth, and the liquid condensate flows downward. Due to the large amount of latent heat released in vapor condensation the vapor-liquid counterflow can generate large rates of heat flow with small (or even vanishing) net mass transport.

The model developed by White and his associates gives a qualitative picture of the workings of a vapor-dominated reservoir, but it does not quantify the thermohydrological conditions and mechanisms, or the genesis of this type of system over geologic time. One of the most important parameters in a vapor-dominated reservoir is the amount and distribution of pore water. This is of great practical significance in the exploitation of these systems, as their longevity will depend on the fluid reserves in place. Though liquid has been directly encountered only in condensation zones near the reservoir margins there is convincing evidence that in the natural state very substantial amounts of liquid are present in vapor-dominated reservoirs. This can be most convincingly shown from mass balance considerations, which demonstrate that fields like Larderello, Italy, and The Geysers, California, would have to have an unreasonably large reservoir thickness if the extracted fluids had been stored in the form of steam (James, 1968; Nathenson, 1975; Weres et al., 1977; Pruess, Celati, Calore, D'Amore, 1985). However, no direct evidence has been found for the deep water table hypothesized by White et al. (1971), and further suggested by the work of D'Amore and Truesdell (1979).

The small (approximately vapor-static) vertical pressure gradient observed in vapor-dominated systems (Celati et al., 1975), and the fact that discharges consist of saturated or superheated steam, have been widely held as evidence that dispersed water saturation in these systems is near the irreducible limit of perhaps $S_\ell \approx 30\%$ (Grant, 1979; Straus and Schubert, 1981). This conjecture was rejected by Pruess and Narasimhan (1982). Pointing out that all known vapor-dominated reservoirs occur in fractured rock with low matrix permeability (corresponding to the "cracked sponge" model of Weres et al., 1977), Pruess and Narasimhan demonstrated theoretically a mechanism for enhancement of flowing enthalpy, which can cause saturated or superheated steam to be discharged into a fracture system from low permeability rocks with large (mobile) water saturation. Thus, large liquid saturations would be compatible with a small (approximately vapor-static) pressure gradient in the fractures. The hypothesis of large liquid saturations put forward by Pruess and Narasimhan has recently obtained direct support from geochemical observations. From an analysis of non-condensible gas concentrations, it was concluded by D'Amore and co-workers (1982) that a very large fraction of fluids produced at The Geysers, up to 99%, originated from boiling of liquid phase in the reservoir.

In this paper we present numerical modeling studies which are aimed at quantifying some of the key thermohydrological aspects of vapor-dominated reservoirs, namely, the conditions under which a vapor-dominated system can evolve naturally, and the thermodynamic conditions present in its (quasi-) steady undisturbed state. We consider the vertical heat flux in vapor-dominated systems, and show that heat pipes can exist in two distinct states, corresponding to liquid-dominated and vapor-dominated pressure profiles, repectively. Our simulations show that a liquid-dominated heat pipe evolves in a fractured hydrothermal system which is subjected to large vertical heat flux (of the order of 1 W/m^2 on the average). It represents a two-phase geothermal reservoir with vertical temperature and pressure profiles close to the B.P.D. relationship. This type of system can evolve into the vapor-dominated type following a temporary enhancement of vapor discharge through natural vents. Our numerical experiments show that a rather brief and limited discharge event is sufficient to "set the system off" to evolve towards a vapor dominated state.

Our studies are generic rather than site-specific. Although we use fomation parameters and conditions representative of the reservoirs at The Geysers and Larderello, we aim at demonstrating key mechanisms rather than reproducing detailed field observations. We believe, however, that the concepts developed here will be useful for constructing quantitative reservoir engineering models of actual vapor-dominated reservoirs, and for evaluating their response to production and injection operations.

Heat Flow in Vapor-Dominated Reservoirs

Several authors have reported temperature gradients and rates of conductive heat loss in the impermeable cap overlying vapor-dominated reservoirs. Conductive heat flux above The Geysers reservoir ranges from 0.4 W/m^2 in zones with deep steam or poor productivity (Urban et al., 1975; Hite and Fehlberg, 1977) to 4 W/m^2 above shallower steam anomalies (Ramey, 1970). Conductive heat flux as large as 4 W/m^2 has also been reported for Kawah Kamojang (Straus and Schubert, 1981). At Larderello, depth to first steam is typically 500 m (Cataldi et al., 1963; James, 1968), corresponding to an average temperature gradient in the caprock of $< 0.5°C/m$, and a conductive heat flux of typically 1 W/m^2.

Some interesting conclusions can be drawn just on the basis of the magnitude of conductive heat loss. In the natural undisturbed state the rate at which heat is conducted away from the top of a vapor-dominated reservoir must closely equal the rate at which heat is supplied by condensation of steam rising from depth. For a heat flux Q the mass rate of condensation per unit area is $Q/h_{v\ell}$, where $h_{v\ell}$ is the latent heat of vaporization (or condensation). In the natural quasi-steady state the condensate must flow downward at the rate at which it is generated, so that according to Darcy's law

$$\frac{Q}{h_{v\ell}} = \frac{k\, k_{r\ell}\rho_\ell}{\mu_\ell}\,(\rho_\ell g - |dp/dz|) \qquad (1)$$

Here $k.k_{r\ell}$ is the effective vertical permeability for liquid (product of absolute permeability k and relative permeability $k_{r\ell}$), ρ_ℓ and μ_ℓ are liquid density and viscosity, respectively, and g is acceleration of gravity. The vertical pressure gradient $|dp/dz|$ in a vapor-dominated system is negligibly small in comparison to the hydrostatic value $\rho_\ell g$, and may be dropped from Equation (1). Evaluating the terms pertaining to water substance in Equation (1) in the temperature range of interest, we obtain

$$Q = k\, k_{r\ell} \cdot 10^{17}\ \frac{W}{m^4} \pm 6\ \% \qquad (2)$$

$$\text{for } 220°C < T < 270°C$$

Thus, in order to sustain a latent heat supply of 1 W/m^2, we require an effective permeability for downflow of condensate of $k.k_{r\ell} = 10^{-17}\ m^2 = 10\ \mu d$ ($k.k_{r\ell} = 40\ \mu d$ for $Q = 4\ W/m^2$). The permeability of unfractured rock in some vapor-dominated systems may be in this range, or may be somewhat smaller (Pruess and Narasimhan, 1982). If rock matrix permeability is somewhat smaller, then the effective permeability required by Equation (2) can only be attained if there is some residual mobility of liquid water in the fractures, presumably as a thin layer held on (rough) fracture walls by capillarity and adsorption. If such a layer of mobile liquid exists, this would suggest that liquid saturation in the rock matrix is large, as otherwise all liquid would be sucked away from the fractures into the small matrix pores by capillary and adsorptive forces.

Porous Heat Pipes

In Appendix A we have assembled some basic equations for mass and heat flow in porous heat pipes, which are useful for a conceptual model of vapor-dominated systems and for a discussion of simulation results to be presented below. From Equation (A.3) it is possible to compute, for given relative permeability functions $k_{r\ell}(S_\ell)$ and $k_{rv}(S_\ell)$, the vertical pressure gradient dp/dz corresponding to balanced counterflow as a function of liquid saturation S_ℓ. The resulting relationship at a temperature of T = 240°C is plotted in Figure 1 for Corey relative permeabilities (see Table 1). In Figure 1 we have also plotted the corresponding convective heat flux as given by

Equation (A.4). It is seen that for a given heat flux there are in general two possible thermodynamic states of the heat pipe, namely, a liquid-dominated state with large liquid saturation and nearly hydrostatic pressure gradient, and a vapor-dominated state with liquid saturation near the irreducible limit, and nearly vapor-static pressure gradient. The dashed line in Figure 1 corresponds to a convective heat flux of 1 W/m^2 at a vertical permeability of 26.8 x 10^{-15} m^2, which is the average (equivalent) continuum permeability used in the fractured porous medium simulations, below.

It is now well established that present vapor-dominated reservoirs have evolved from liquid-dominated precursors with significantly higher temperatures at depth (see e.g. Sternfeld and Elders, 1982; Hebein, 1983, 1985, and references therein). The actual thermodynamic state of the liquid-dominated precursor, and the nature of the events which "set the system off" to evolve towards a vapor-dominated state, have not yet been determined. Central issues in this regard are the hydrologic setting which is conducive to such an evolution, and the role of geochemical processes in effecting a proper confinement of fluid convection (Hebein, 1985).

We suggest that a likely precursor of a vapor-dominated reservoir is a liquid-dominated heat pipe system in fractured rock with low matrix permeability.

Numerical Simulations

The geological setting in an area of extensional tectonics as well as downhole and core data indicate that most fractures at The Geysers are nearly vertical (Lipman et al., 1977; McLaughlin, 1981). For purposes of numerical modeling we have idealized this situation as follows: we consider two sets of plane, vertical, persistent fractures with D = 50 m spacing, and an angle of 90° between them. The rock matrix consists of vertical slabs, assumed to be 500 m in height, with a square cross section of 50 x 50 m^2. A plan view of the model system is given in Figure 2, while Figure 3 shows a vertical section parallel to one of the fracture sets. Assuming a system of large areal extent (linear dimensions large compared to fracture spacing), it is sufficient to model one symmetry element, consisting of one rock slab and (half of) its surrounding fractures. For modeling purposes the flow domain is discretized into 11 layers, with thickness varying from 10 m at the top and bottom boundaries to 100 m away from the boundaries. The rock matrix in each layer is discretized into eight nested volume elements, which are defined according to the method of "multiple interacting continua" ("MINC"; Pruess and Narasimhan, 1985) on the basis of distance from the fractures, as schematically shown in Figure 2. The parameters used in the calculations were chosen representative of The Geysers (Ramey, 1970; Lipman et al., 1977; Dykstra, 1981; Pruess and Narasimhan, 1982); they are summarized in Table 1. Most of the parameters are based on results of laboratory or field tests, but some important ones are unknown and require ad hoc assumptions. For the fractures we assume a linear dependence of relative permeabilities on phase saturation, with irreducible saturations of 0.01 for vapor and liquid. Following White et al., (1971) and Truesdell and White (1973) we expect that (negative) suction pressures on the liquid phase from capillary and adsorptive forces will play an important role in keeping liquid preferentially in the rock matrix. No information has been published on the dependence of suction pressure on saturation (and temperature) for the rocks encountered in vapor-dominated systems. We rather arbitrarily choose a linear dependence of suction pressure on saturation, with a maximum strength of 10^5 Pa = 1 bar, which we consider a conservative (small) value. We furthermore assume that the range of suction pressures encountered upon desaturating the fractures is equal to that in the matrix (i.e., $0 > p_{suc} > -1$ bar), the sole difference being that in the fractures these suction pressures occur over a narrow range of small liquid saturations (Pruess, Tsang, Wang, 1985). Thus, suction equilibrium between matrix and fractures is possible locally over the entire range of liquid saturations $0 < S_\ell < 1$ in the matrix. The saturation cutoff at which suction pressure goes to zero in the fractures was chosen as $S_\ell = 0.011$, which is slightly larger than the assumed irreducible liquid saturation of 0.01. With this choice of cutoff there exists a small saturation interval $0.01 < S_\ell < 0.011$ with mobile liquid at non-zero suction pressures in the fractures.

The simulations were carried out with our general purpose simulator MULKOM (Pruess, 1983). The pore fluid was assumed to be pure water, with no allowance for non-condensible gases, dissolved solids, or rock-fluid interactions.

Results

An overview of the simulated cases is given in Table 2. We begin with a single phase liquid system in gravitational equilibrium. Initial temperature was chosen equal to 240°C throughout, and a boundary condition of T = 240°C, p = p_{sat} (240°C) is maintained at the top. At the bottom heat is injected into the fracture system at an average areal rate of 1 W/m^2, while the bottom of the rock column is modeled as a no flow boundary (Figure 3). In response to the heat injection the reservoir goes through a transient period, expelling some fluid into the caprock and attaining two-phase conditions throughout the fractures. After approximately 2,000 years a steady state is reached which can be described as a liquid-dominated heat pipe: the fractures are in two-phase conditions throughout, with small vapor saturation $1.15\% < S_v < 1.28\%$, so that both vapor and liquid are mobile in the fractures. Temperature and pressure conditions closely approximate a B.P.D. profile; vertical pressure gradients are approximately 0.04% below hydrostatic, permitting a downflow of liquid to balance the upflow of steam. Average vapor saturation in the entire reservoir is .088%. The rock matrix is entirely water saturated, except at the upper boundary, where two-phase conditions with a maximum vapor saturation of 5.9% are present. Fractures and rock matrix are in a highly equilibrated state, with maximum differences in temperatures and pressures no larger than 0.5°C and 0.05 bars, respectively, at any given depth.

The liquid-dominated heat pipe system will remain in its steady state indefinitely, unless it is disturbed by some "event" which causes changes in reservoir parameters or boundary conditions. A plausible event which could initiate a transition from liquid-dominated to vapor-dominated heat pipe may be the opening of high-permeability conduits in the caprock, through which vapor can be discharged to the surface. Such vents may be created by tectonic movement. We have used numerical simulations to determine whether a rather limited and credible discharge event can in fact perturb the fractured liquid-dominated heat pipe in such a way that it will evolve into a vapor-dominated system. In our calculations a discharge event is represented in a rather schematic way. We subject the liquid-dominated system to fluid discharge from the top of the fractures at a constant rate of 40 kg/s.km^2. This rate is comparable to estimated natural discharge at many geothermal fields.

The imposed fluid discharge gives rise to rapid transients in the system, with conditions of increased vapor saturation propagating downward in the fractures as boiling spreads throughout the matrix. After one year of discharge the reservoir is depleted of 4.16% of original fluid reserves, and is boiling throughout, with vapor saturations in the top 50 m of the fractures in excess of 98%. We terminate mass discharge rather arbitrarily after 606.6 days (corresponding to depletion of 6.76% of original fluid reserves), at which time vapor saturation exceeds 96% throughout the fractures. In response to discharge-induced boiling, temperatures in parts of the fractures drop by as much as 19°C. Average decline of reservoir temperatures is 5.5°C. A considerable imbalance develops between fractures and rock matrix, with differences in temperatures and pressures as large as 18.4°C and 19.4 bars, respectively, at a given elevation. While there is a general decline of temperatures in response to the discharge, the top of the fracture network is actually heating up (from 240.5 to 252.0°C). This phenomenon is caused by the very large rates of vapor upflow. As vapor saturation and mobility throughout the fractures increase in response to discharge, the nearly hydrostatic vertical pressure gradient drives vapor upward at a rate in excess of the applied discharge to the surface. As this vapor condenses at the top, temperatures increase, and large liquid saturations in the matrix are attained beneath the caprock.

After terminating the mass discharge we maintain the T = 240°C upper boundary, but assume it "sealed"; i.e., there is no mass flux across the reservoir top. Heat recharge into the bottom of the fractures continues at an average areal rate of 1 W/m^2. The system goes through a non-monotonic evolution, involving an overall cooling trend with some intermittent temperature increases in parts of the fracture system. Top and bottom temperatures are plotted in Figure 4, which also shows that for an extended period of time there is a net (conductive) heat loss of 1.6 W/m^2. After approximately 440 years net heat loss rates begin a steep decline, and after 1460 years the rate of heat loss at the reservoir top is only 0.4% above the rate of heat recharge at the bottom, indicating close approach to a steady state. Figure 4 shows that these conditions are reached after 500 time steps, and that subsequently our calculation advances only extremely slowly in time, while producing oscillatory variations in temperatures at the bottom of the fractures on a time scale of 1-2 years. These are accompanied by mild fluctuations in the (small) rate of net heat loss. (We chose to plot the parameters in Figure 4 as function of time step index rather than physical time in order to be able to display these features). What is happening in the calculation is that all thermodynamic parameters in the fractures and rock matrix are steady to within 3 or more digits, corresponding to a steady vapor-dominated state, while the fractures in the bottom layer of our calculational mesh keep going through repeated transitions between liquid- and vapor-dominated conditions. The small time period of these cycles, and the fact that they involve a change in liquid saturation in the bottom of the fractures over almost the entire two-phase range ($0.01 < S_\ell < 0.99$) slows the progress of the calculation in physical time down severely. We have not yet been able to determine whether the cycling at the bottom of the fractures is an artifact of our boundary conditions or spatial discretization, or whether it is a "real" effect, caused by the different response times of rock matrix and fractures to temperature and pressure changes.

At any rate, the state reached after 600 time steps (1460 years) is very close indeed to a steady state, with conductive heat loss at the top matching heat recharge at the bottom to within 0.4%. This state represents a vapor-dominated heat pipe, with a vertical pressure gradient approximately 10% above the vapor-static value. Vapor saturation in the fractures is near 98.9% throughout, with liquid saturation being slightly above the irreducible limit of 1%, so that both phases are mobile in the fractures. Average liquid saturation in the reservoir is 89.1%. Figure 5 shows liquid saturations (in percent) in the rock matrix in the vapor-dominated steady state. Single phase liquid conditions are present near the bottom and at the top, while through most of the rock matrix liquid saturations are near 89%. Total temperature and pressure variations in the fracture system over 500 m depth are 1.5°C and 1 bar, respectively. Fractures and rock matrix are generally in approximate thermodynamic equilibrium, with temprature and pressure differences of less than 0.2°C and 0.1 bar, respectively, at all depths except near the reservoir top, where these differences are as large as 2.9°C and 1.2 bars.

The simulated pattern of fluid flow in the vapor-dominated state is as follows. Vapor rises in the fractures at an average rate of 0.56 kg/s.km^2, and in doing so partly condenses on the fracture walls. Most of the condensate flows downward in the fractures, but some of it enters the rock matrix aided by suction forces. A smaller fraction of the rising vapor enters the rock matrix, especially at shallower elevations, where it also condenses. Inside the rock matrix liquid flows downward and, near the lower boundary, outward into the fractures. The heat released by the condensing vapor is transferred to the rock matrix, and eventually escapes by conduction at the top of the system.

Discussion and Conclusions

The calculations reported here demonstrate what we believe to be a plausible scenario for the evolution of a liquid-dominated reservoir in fractured rock into a system of the vapor-dominated type. We wish to emphasize some of the limitations and ad hoc assumptions of our study, which should be investigated in future modeling work. No description is made of geochemical processes with mineral redistribution; the all-important lateral self-sealing of the system, and the sealing of the caprock following a discharge event, are simply assumed and not modeled. Also, no description is made of the "deep end" of the system, where uncertainties about fluid and heat transport mechanisms are greatest; instead, simple boundary conditions were imposed at 500 m below the reservoir top. A realistic reservoir thickness may be larger, perhaps 2000 m; as we did not include a description of the "deep end" anyway, we considered it appropriate to simplify calculations by modeling a smaller domain of only 500 m vertical extent. The venting period imposed on the liquid-dominated precursor system was modeled rather schematically, assuming a constant mass rate of discharge. In a more realistic description, discharge rate would be permitted to adjust according to fluid pressures and permeability of flow channels (vents) towards the surface. When a vent opens up, perhaps in response to a tectonic event, discharge will commence at some rate, and will actually increase with time even if the permeability of the vent remains constant. This occurs because discharge causes vigorous boiling in the fractures, and increased vapor mobility to greater depth, so that higher pressure steam is being tapped. In reality we would expect the increasing pressurization and discharge of a vent to enhance its permeability by clearing debris and widening flow channels, giving rise to a positive feedback on discharge rate which may result in a hydrothermal eruption.

It should also be pointed out that in a "real" system there will be a finite rate of fluid recharge, with net mass loss reflecting the difference between discharge and recharge rates. There is no reason why the steam-water counterflow should be perfectly balanced, as assumed in our model for simplicity; instead it is likely that there is a net mass upflow (and discharge) in the central zone of a vapor-dominated field, while we expect net downflow in the condensation zones near the reservoir margins.

In a detailed modeling study as reported here it is necessary to quantitatively specify a number of parameters which are poorly known. A case in point are the "characteristic curves" (relative permeability and suction pressure) in the fractures. In future modeling studies we intend to examine the sensitivity of system behavior to these as well as other parameters, such as fracture and matrix permeability, fracture spacing, and boundary conditions.

While some of the quantitative details are subject to considerable uncertainty, we believe that some general conclusions can be drawn from our numerical experiments. When a liquid-dominated hydrothermal system in fractured rock is subjected to large heat influx at the bottom, of the order of $1 W/m^2$, it will evolve into a two-phase heat pipe system with vertical pressure and temperature trends closely following the boiling point-for-depth (B.P.D.) relationship. This system is in a steady state which is stable against small perturbations. However, a relatively minor discharge event (venting), involving the release of not more than a few percent of the original mass in place over a time span of months or a few years, will give rise to a very strong perturbation of system conditions in the network of high-permeability fractures. The perturbation in the fractures controls subsequent system evolution after the venting terminates, causing the eventual attainment of a vapor-dominated steady state with small (nearly vapor-static) vertical pressure and temperature profiles. Average water saturation in this state can be of the order of 90%.

In contrast, a vapor-dominated heat pipe in an unfractured porous medium would only be possible if most of the original liquid in place were discharged from the system, so that liquid saturation would decline to values near the irreducible limit of perhaps S_ℓ = 30%. This would require a massive discharge over extended periods of time; furthermore, vertical saturation profiles during this discharge would have to remain nearly uniform to permit a vapor-dominated heat pipe to evolve. We consider it improbable that these constraints could in fact be realized in a natural hydrothermal convection system. We suggest, therefore, that vapor-dominated reservoirs can only form in a hydrological setting characterized by dual permeability, where a high-permeability network of interconnected fractures with small volume provides pressure control in the system, while most of the fluid reserves are stored in liquid form in a porous rock matrix of low permeability.

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Appendix A: Vapor-liquid counterflow.

Counterflow of vapor (upwards) and liquid (downwards) occurs under conditions where the vertical pressure gradient is intermediate between vapor-static and hydrostatic values. Assuming that the z-coordinate axis points upward, this condition can be written

$$\rho_v g < -\frac{dp}{dz} < \rho_\ell g \qquad (A.1)$$

(All symbols are defined in the text, following Equation (1)). When upward vapor flux is equal to downward liquid flux, net vertical mass transport is zero. The condition for "balanced counterflow" can be written

$$F_v = -F_\ell \qquad (A.2)$$

or, from Darcy's law,

$$-\frac{k_{rv}\rho_v}{\mu_v}\left(\frac{dp}{dz} + \rho_v g\right) = \frac{k_{r\ell}\rho_\ell}{\mu_\ell}\left(\frac{dp}{dz} + \rho_\ell g\right) \qquad (A.3)$$

The upward convective heat flux (Q) corresponding to balanced counterflow is

$$Q = -k\frac{k_{rv}\rho_v}{\mu_v} h_{v\ell}\left(\frac{dp}{dz} + \rho_v g\right) \qquad (A.4)$$

Table 1. Parameters for Numerical Simulations

Parameter	Value
Rocks	
grain density	ρ_R = 2400 kg/m^3
heat conductivity	K = 2.1 W/m°C
specific heat	C_R = 960 J/kg°C
porosity	8%
permeability	$k_m = 3 \times 10^{-18}$ m^2
thickness	500 m
relative permeability: (Corey curves)	liquid $k_{r\ell} = (S^*)^4$ vapor $k_{rv} = (1 - S^*)^2 (1 - (S^*)^2)$ where $S^* = (S_\ell - 0.3)/0.65$
suction pressure	$p_{suc} = -10^5 (1 - S_\ell)$ Pa
Fractures	
two vertical orthogonal sets	
width	$\delta = 2 \times 10^{-3}$ m
spacing	D = 50 m
porosity per fracture	ϕ_f = 50%
permeability per fracture	$k_f = 3.35 \times 10^{-10}$ m^2
equivalent continuum porosity	$\bar{\phi}_f \approx 2\phi_f\delta/D = 4 \times 10^{-5}$
equivalent continuum permeability	$\bar{k}_f \approx 2\, k_f\delta/D = 26.8 \times 10^{-15}$ m^2
relative permeability	liquid $k_{r\ell} = (S_\ell - 0.01)/0.99$ vapor $k_{rv} = (0.99 - S_\ell)/0.99$
suction pressure	$p_{suc} = \begin{cases} -10^5 (0.011 - S_\ell)/0.011 \text{ Pa for } S_\ell < 0.011 \\ 0 \text{ otherwise} \end{cases}$

Table 2. Overview of Simulations

simulated process	physical time (years)	result	final average liquid saturation: fractures	final average liquid saturation: entire reservoir
heating of reservoir in response to heat flux entering fractures at bottom; mass loss into caprock	2032.3	liquid-dominated two-phase reservoir (steady state)	98.82%	99.91%
venting from top of fractures at a rate of 40 kg/s.km^2	1.66	highly perturbed conditions in fractures	2.5%	92.3%
evolution of reservoir with sealed caprock and continued heat injection at bottom	1468.5	vapor-dominated two-phase reservoir (steady state)	1.1%	89.1%

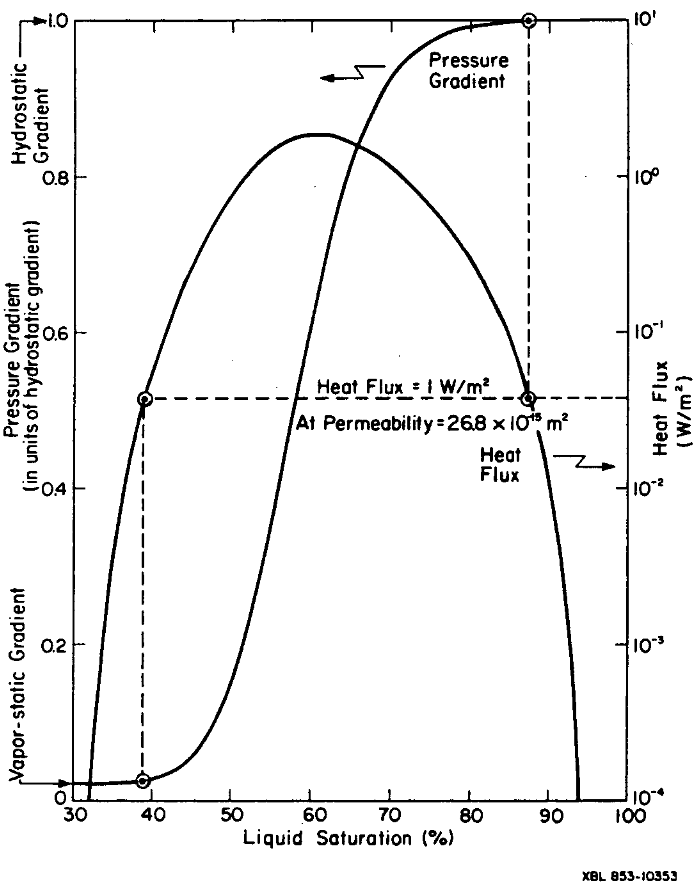

Figure 1. Heat flux and pressure gradient in a vertical porous heat pipe. Heat flux is proportional to permeability, and is here plotted for a permeability of 10^{-15} m^2 (= 1 md).

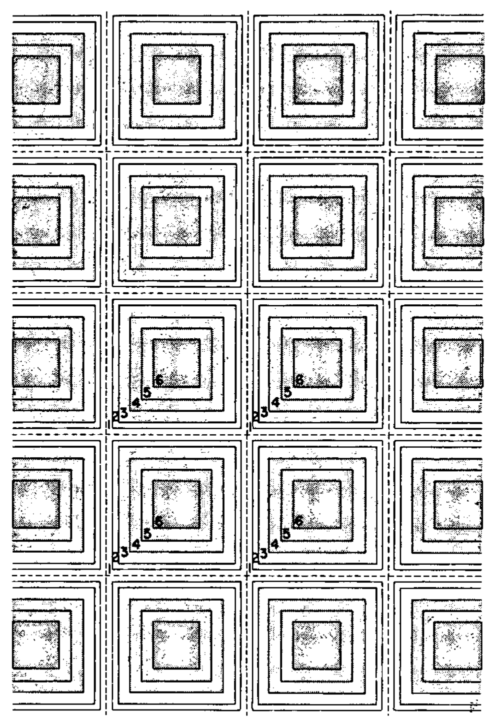

Figure 2. Plan view of our idealized reservoir model. Dashed lines indicate (vertical) fractures. Discretization of the rock matrix blocks is also shown.

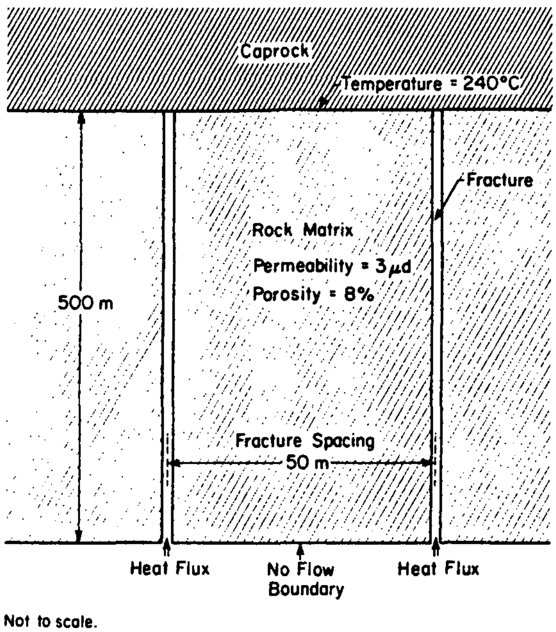

Figure 3. Vertical section through our reservoir model.

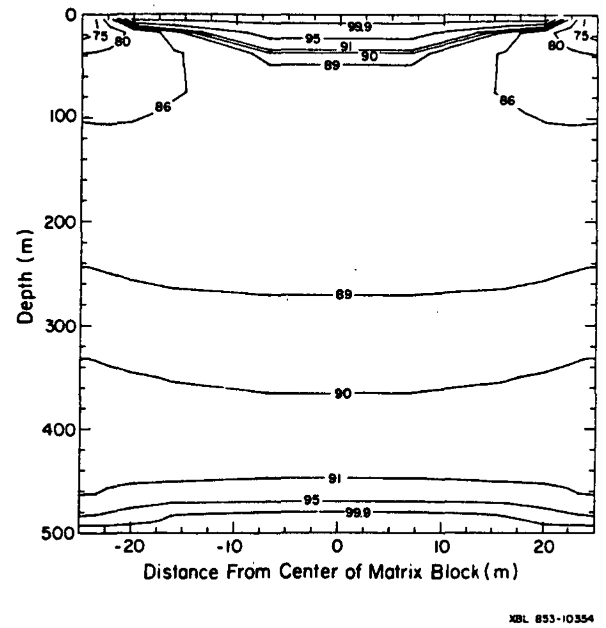

Figure 5. Contours of liquid saturation (in %) in the rock matrix in the vapor-dominated steady state. Note that the horizontal scale is exaggerated tenfold.

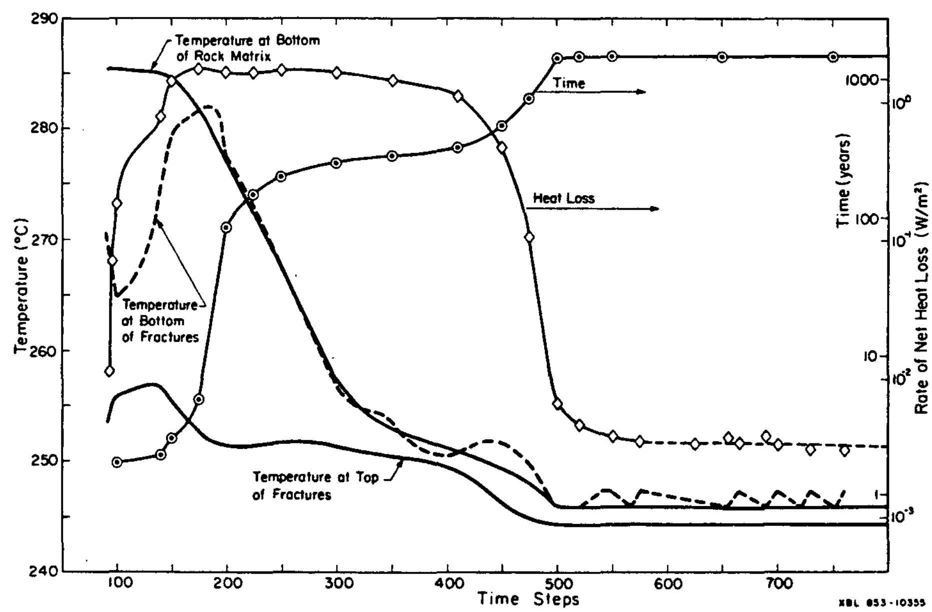

Figure 4. Temporal evolution of selected system parameters after end of venting period. The time steps are counted from beginning of venting period. Venting is terminated and caprock sealed after 90 time steps, corresponding to a time of 606 days.