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UNSTABLE HEAT PIPES

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ABSTRACT

Heat pipes are an important feature of models of vapor-dominated geothermal reservoirs. Numerical experiments reveal that a vapor-dominated heat pipe is unstable if pressure is controlled at shallow levels. This instability is discussed in physical terms, and some implications for geothermal reservoirs are considered.

INTRODUCTION

A heat pipe is here taken to be a porous medium in which heat is transferred vertically from depth by the mechanism of steam rising and condensing at the top, and liquid condensate falling to the bottom to boil again. The steam and liquid gravity driven counterflow is balanced so that there is no net mass transfer (Pruess, 1985; White et al, 1971; Straus and Schubert, 1981).

The heat pipe is central to conceptual models of vapor-dominated geothermal reservoirs (White et al 1971; Truesdell and White, 1973, Pruess and Narasimhan, 1982). In the main reservoir pressure and temperature do not vary greatly with depth and heat transfer is convective. A low permeability cap rock overlies the reservoir. Steam rises through the main reservoir and condenses at the cap rock, releasing its latent heat of vaporisation. The condensate trickles back down through the main reservoir, to an underlying boiling liquid surface. Net mass transfer through the main reservoir is small. Fields described by this conceptual model include Larderello, Italy; The Geysers, California; Matsukawa, Japan; and Kawah Kamojang, Indonesia.

In numerical simulations of one-dimensional vertical heat pipes, it is usual to fix the pressure and saturation at one end, and to specify a heat input or output (and zero mass transfer) at the other. This paper has been motivated by the observation that in order for a numerical simulation to converge to a steady vapor-dominated heat pipe it is necessary to have the constant pressure and saturation condition at the bottom end.

Further simulations have confirmed that the vapor-dominated heat pipe is unstable if the constant pressure and saturation condition is at the top. If this is perturbed, it either switches to a liquid-dominated heat pipe or dries out. If the constant pressure and saturation condition is at the bottom, the vapor-dominated heat pipe is stable to small perturbations. A liquid-dominated heat pipe has the reverse stability requirement — it is stable when the constant pressure and saturation condition is at the top and unstable otherwise.

Aside from the insights gained into two-phase vertical flow, this has some interesting implications for geothermal reservoirs. If the reservoir can be viewed as a one-dimensional porous medium with two-phase fluid and negligible mass through-flow these results suggest that a reservoir will only be vapor-dominated if the pressure control is at depth. That is, a vapor-dominated reservoir will have good recharge at depth and poor communication at its top (for example, a caprock). Conversely, a liquid-dominated reservoir will be expected to have good recharge at the top and relatively poor recharge from depth. These results say little about reservoirs where two-dimensional or three-dimensional flow effects are important, or about fractured reservoirs in which there is pressure support distributed throughout in blocks. An assumption implicit in these comments is that the reservoir is not still evolving, but has reached a stable steady state (this may take thousands of years).

SOME THEORY

Conductive effects are ignored here for simplicity. If the equations for mass and energy conservation are solved for a steady state one-dimensional vertical heat pipe, the convective heat flux may be shown to be (for example, Pruess et al, 1986)

$$Q = \frac{k(\rho_l - \rho_v)h_{vl}g}{\nu_l/k_{rl} + \nu_v/k_{rv}} \tag{1}$$

where k is the permeability of the porous medium, ρ is density, g is the gravitational constant, h_{vl} is the latent heat of vaporisation, ν is the kinematic viscosity, k_r is the relative permeability, and subscripts l and v mean liquid and vapor phase respectively.

The relative permeability functions k_{rl} and k_{rv} reflect experimental evidence that when there is a large amount of steam present, it is more difficult for the liquid phase to flow. When the quantity of liquid present is small enough, it will not flow. The residual liquid saturation, below which the liquid phase is immobile, is around 0.3 for sands, and may be as high as 0.8 for fractured geothermal reservoirs (Grant and Glover, 1984; Pruess et al, 1986, p.4; Pruess and Narasimhan, 1985; Pruess, 1985). The dependence of k_{rl} and k_{rv} on the liquid saturation S is not well known. For simplicity in this paper it has been assumed that

$$k_{rl} = \begin{cases} 0, & 0 \le S < 0.3 \\ 1 - (1 - S)/0.7, & 0.3 \le S \le 1.0 \end{cases}$$

$$k_{rv} = 1 - k_{rl}$$

The exact form of the relative permeability function is unlikely to affect the nature of the instability under study here.

Given a vapor-dominated heat pipe there is a liquid-dominated heat pipe with the same heat flux Q. This may be seen either from the form of Equation 1 or from Figure 1, in which Q is plotted against liquid saturation S for typical parameter values. When S is small (just above residual liquid saturation), the heat pipe is vapor-dominated, and the vertical pressure gradient is just above vaporstatic. When S is near 1 the heat pipe is liquid-dominated with the pressure gradient just below hydrostatic. These features are nicely summarised in Darcy's equations for two-phase flow,

$$u_l = -\frac{kk_{rl}}{\nu_l}(\nabla p - \rho_l g) \tag{2}$$

$$u_v = -\frac{kk_{rv}}{\nu_v}(\nabla p - \rho_v g) \tag{3}$$

where u is the mass flux density, and p is pressure.

NUMERICAL EXPERIMENTS

The simulator MULKOM (Pruess, 1983) was used to investigate the stability of heat pipes. The reservoir parameters chosen are listed in Table 1. A sketch of the computer model is in Figure 2. Both liquid and vapor-dominated heat pipes have been studied, but for brevity only the vapor-dominated results are discussed in any detail here.

A steady vapor-dominated heat pipe was set up by placing the large (almost constant p, S) element at the bottom and specifying heat extraction at the top, and starting with a column of two-phase fluid that had vaporstatic pressures and was close to residual liquid saturation. This quite quickly settles to a steady vapor-dominated heat pipe. When it is perturbed, by changing the amount of heat extracted at the top by a small amount, it adjusts to the new heat flux, remaining close to the original configuration. This behaviour we term stable.

The boundary conditions on this vapor-dominated heat pipe were then changed — the top element was made very large (almost constant p, S) and the heat flux was specified by the heat input at the bottom element, which was made the same size as most of the other elements in the column (see Figure 3). This configuration, when not perturbed, remained steady for a long time.

A small perturbation was then introduced by changing the amount of heat input at the bottom. The response of the heat pipe was not small. If the heat input was reduced, the heat pipe became liquid-dominated (and stable). If the heat input was increased, the heat pipe gradually dried out and would never stabilise without conductive terms present.

RESULTS

The switch from the vapor-dominated configuration to a liquid-dominated heat pipe is here discussed in more detail. Figure 4 is a plot of the flowing enthalpy at each element at various times after the heat was turned down at the bottom element. The initial heat input is 1 W/m^2. This is perturbed down to 0.9 W/m^2 at time zero. A notable feature of the plot is that the flowing enthalpy drops to a value less than 0.9 W/m^2, and the whole heat pipe stabilises temporarily at this value, before finally moving to match the heat input of 0.9 W/m^2. This final stabilisation corresponds to a switch to a liquid-dominated heat pipe as may be seen in Figure 5. The liquid saturation remains near the residual value of 0.3 until late in the simulation, then moves up to near 1 (liquid-dominated) when the heat pipe finally becomes stable.

Figure 6 shows that the heat pipe initially moves from zero net mass flow to a net downflow under the influence of the imposed perturbation. A look at the liquid and vapor phase flow rates in Figures 7 and 8 respectively, reveals that the net downflow is largely due to a reduction in steam upflow. These flow rates stabilise temporarily, and are responsible for the behaviour of the flowing enthalpy discussed previously. Finally, the liquid downflow rate reduces to once again match the steam upflow rate, when the heat pipe becomes liquid-dominated. For completeness the pressure changes that drive these flowrate changes are presented in Figure 9.

Parameter	Value
porosity	0.2
permeability	100 millidarcies
rock density	2650 kg/m^3
conductivity	0.0
rock specific heat	1.0 J/kg°C

Table 1: Parameters Used in Heat Pipe Simulations

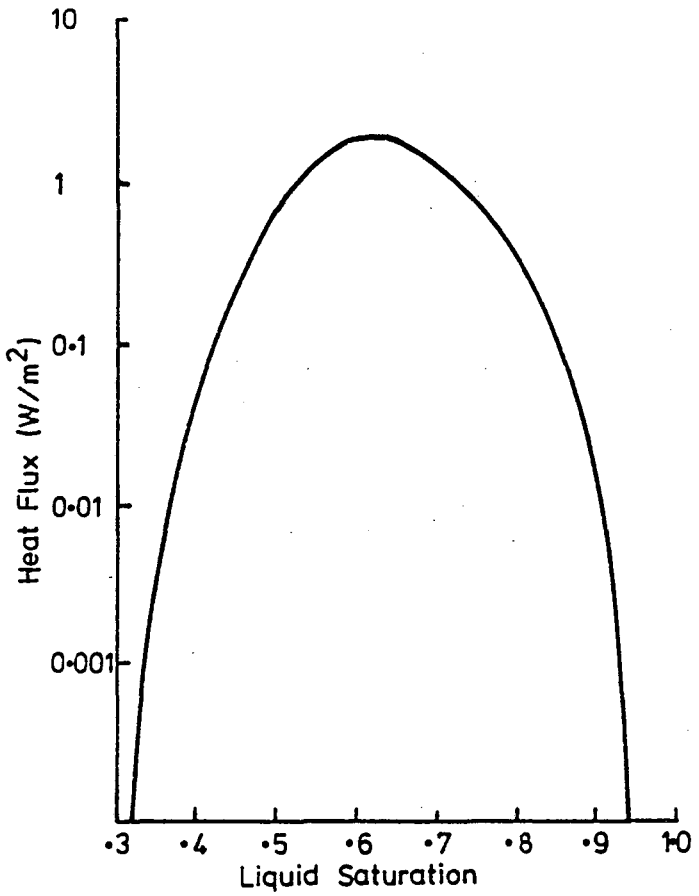

Figure 1. The heat flux in a steady vertical heat pipe. This plot is taken from Pruess (1985), and is for Corey relative permeability curves and a permeability of 1 md. The shape will be similar for the case studied here.

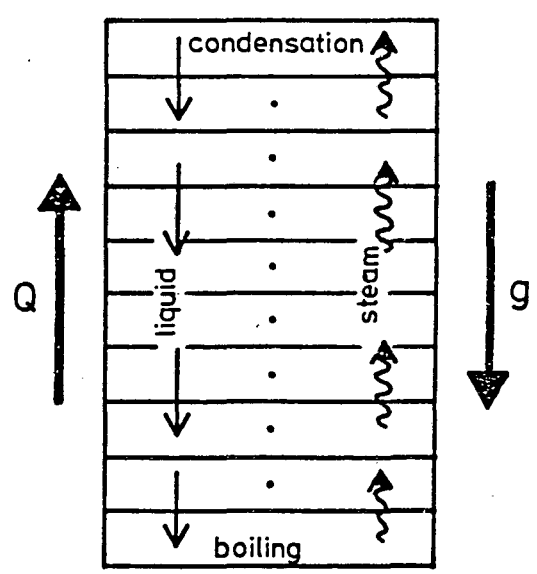

Figure 2. The computer model of a heat pipe used here. The heat pipe is 100 m long, and has 10 computational elements. An additional large element is placed at the appropriate end to fix pressure and saturation there. A heat input or output is specified at the other end.

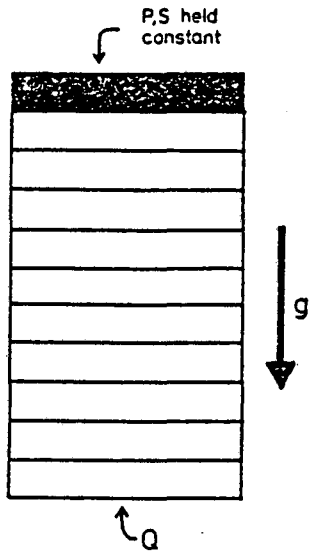

Figure 3. The specific computer model of an unstable vapor-dominated heat pipe used here. Pressure and saturation are held constant at the top, and heat is applied to the bottom.

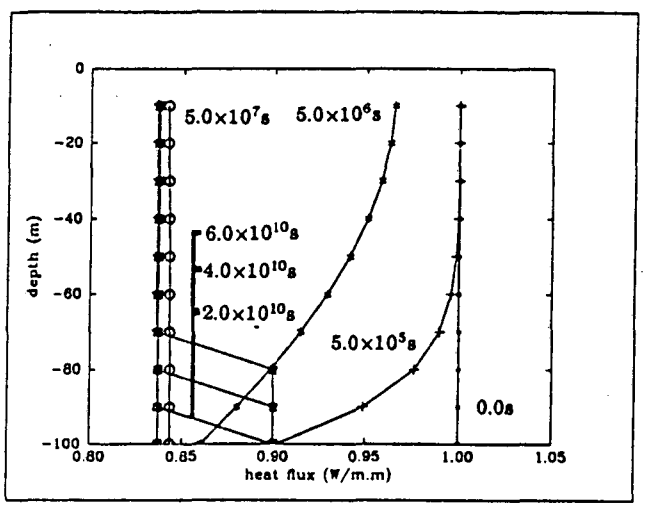

Figure 4. The flowing enthalpy in the unstable vapor-dominated heat pipe, at various times after the heat input is reduced. The initial conditions corresponded to a steady heat flux of 1 W/m^2.

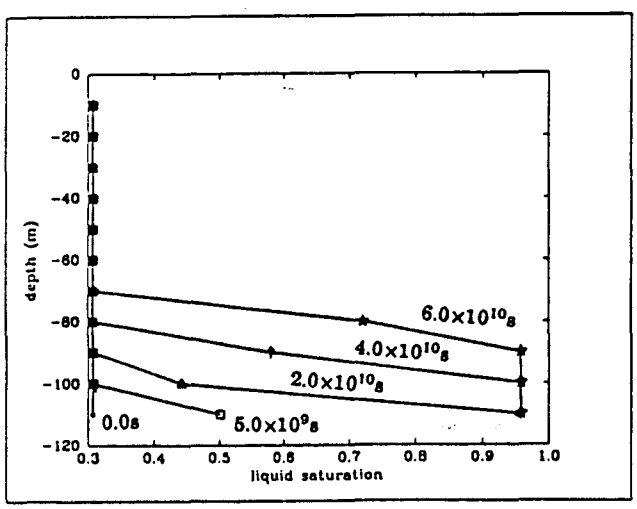

Figure 5. The liquid saturation in the unstable vapor-dominated heat pipe, at various times after the heat input is reduced. The initial conditions corresponded to a steady heat flux of 1 W/m^2.

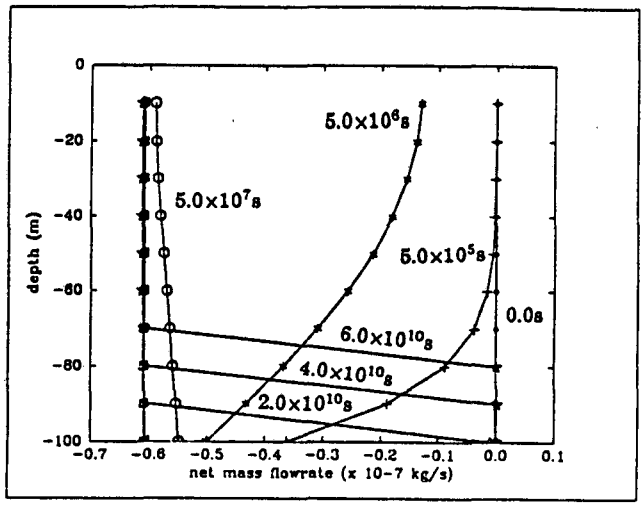

Figure 6. The net mass flowrates in the unstable vapor-dominated heat pipe, at various times after the heat input is reduced. The initial conditions corresponded to a steady heat flux of 1 W/m^2, and zero net mass flow.

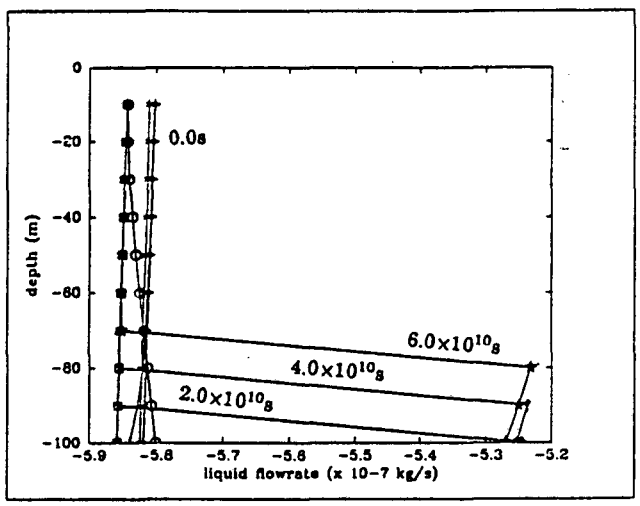

Figure 7. The liquid flowrates in the unstable vapor-dominated heat pipe, at various times after the heat input is reduced. The initial conditions corresponded to a steady heat flux of 1 W/m^2. Negative values indicate downflow.

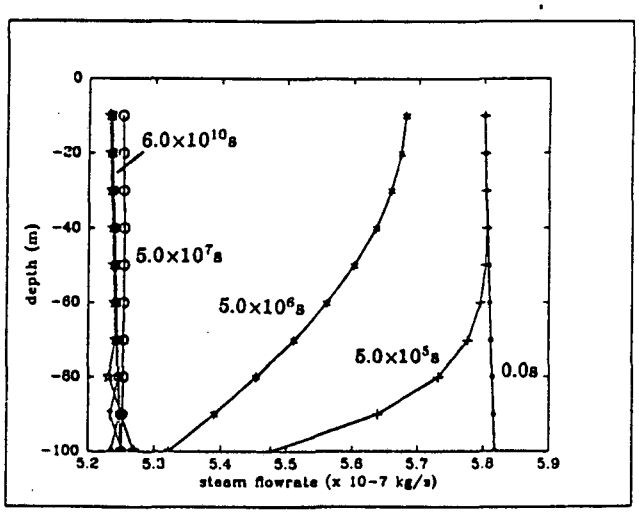

Figure 8. The steam flowrates in the unstable vapor-dominated heat pipe, at various times after the heat input is reduced. The initial conditions corresponded to a steady heat flux of 1 W/m^2. Positive values indicate upflow.

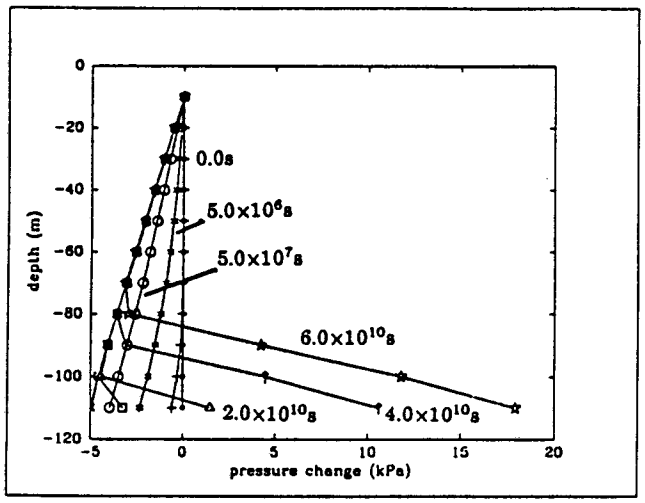

Figure 9. The changes in pressure in the unstable vapor-dominated heat pipe, at various times after the heat input is reduced. The initial conditions corresponded to a steady heat flux of 1 W/m^2, and a near vapor-static pressure gradient. The pressure changes plotted are the differences from the initial values.

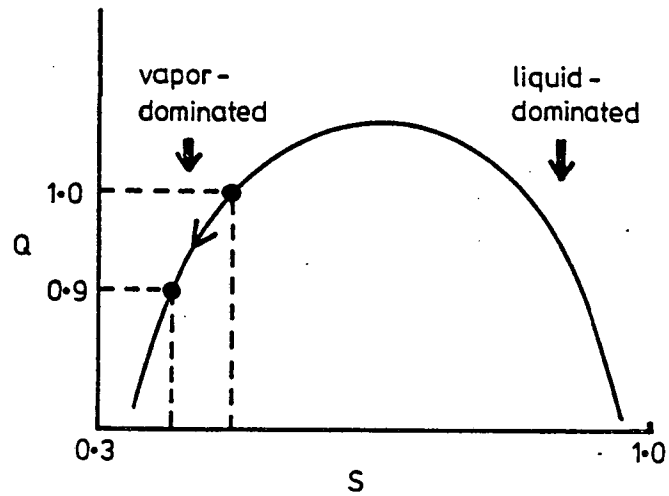

Figure 10. A sketch of heat flux vs. liquid saturation in a steady vertical heat pipe, illustrating that for a vapor-dominated heat pipe, if the heat flux Q is reduced the steady-state liquid saturation is smaller.

DISCUSSION

When the heat input is reduced at the bottom of the heat pipe, it cools there. Since the fluid is two-phase, a drop in temperature must be accompanied by a drop in pressure as they are related by the Clausius-Clapeyron curve. This pressure drop, as seen in Figure 9, diffuses throughout the heat pipe. Since the relative permeability to liquid is small, this pressure drop has a much greater effect on the steam upflow rate than on the liquid downflow rate. The amount of steam leaving the bottom reduces, while the liquid flow rate remains constant. Hence the liquid saturation at the bottom begins to increase.

This increase in liquid saturation is a move in the wrong direction, according to the plot of Q versus S sketched in Figure 10. A stable vapor-dominated heat pipe with the heat flux of 0.9 W/m^2 would have a *smaller* liquid saturation than the initial saturation corresponding to 1 W/m^2. This implies that the current configuration is unstable.

The liquid saturation continues to increase at the bottom element, and eventually causes a pressure increase there. The energy needed for the accompanying temperature increase is supplied by the difference between the heat input at the bottom (0.9 W/m^2) and the amount of heat flux up the heat pipe (0.84 W/m^2).

OTHER RESULTS

When the heat input to the vapor-dominated heat pipe of Figure 3 is *increased*, it simply boils dry from the bottom, and will not stabilise without conductive terms present. The temperature and pressure at the bottom increase, and there is a net mass upflow, due largely to an increased steam flowrate. The bottom element becomes dry steam, and the simulation will not proceed beyond that stage without conduction effects to transfer heat through the bottom element.

Hence the vapor-dominated heat pipe of Figure 3 is unstable — increasing or decreasing the heat input by a small amount destroys the heat pipe.

When the constant pressure and saturation condition is moved to the bottom element in Figure 3, and heat extraction is specified at the top, the vapor-dominated heat pipe is stable to small changes in heat extraction. Small increases or decreases in heat extraction rate lead to small changes in pressure and saturation, and the heat pipe remains vapor-dominated.

A liquid-dominated heat pipe has the opposite stability requirements. If the pressure and saturation are held constant at the top as in Figure 3, it is *stable* to perturbations in heat input. If the constant pressure and saturation condition is at the bottom, the liquid-dominated heat pipe switches to a vapor-dominated heat pipe if the heat output is decreased, or becomes filled with single-phase fluid if the heat output is increased at the top. The kind of argument presented in the discussion above for a vapor-dominated heat pipe also explains the responses of a liquid-dominated heat pipe.

CONCLUSIONS

Vapor-dominated heat pipes are unstable if pressure control is at the top and liquid-dominated heat pipes are unstable if pressure control is at the bottom. This instability is understood physically in terms of Darcy's Law, thermodynamics and the conservation equations. The numerical experiments partly discussed here present a challenge for the applied mathematician, to mathematically explain them.

The implication for geothermal reservoirs is that if vertical processes are dominant, a vapor-dominated reservoir is pressure controlled at depth, while a liquid-dominated reservoir is most likely pressure controlled at shallow levels. This will be of some help in shaping conceptual and computer models of geothermal reservoirs.

There is increasing evidence that fractures and low permeability blocks play an important part in vapor-dominated reservoirs (see for example Pruess, 1985). The response time to perturbations in the fracture system will be much faster than in the blocks. The blocks will act as a distributed delayed source of mass and heat, making the stability issue much more complicated. Extension or adaption of the approach used here for a homogeneous porous medium to a fractured porous medium would be a challenging and fruitful task.

REFERENCES

Grant M. A., Glover R. B. (1984) *Two-phase heat and mass transfer experiment at well BR21 Broadlands,* Geothermics 13 (1984) 193–213.

Pruess K. (1983) *Development of the general purpose simulator MULKOM,* Annual Report 1982, Earth Sciences Div., Report LBL-15500, Lawrence Berkeley Laboratory.

Pruess K. (1985) *A quantitative model of geothermal reservoirs as heat pipes in fractured porous rock,* Transactions of 1985 Symposium on Geothermal Energy, Geothermal Resources Council 1985 Annual Meeting, Volume 9 — Part II, pages 353–362.

Pruess K., Celati R., Calore C., Cappetti G. (1986) *On fluid and heat transfer in deep zones of vapor-dominated geothermal reservoirs,* Report LBL-22810, Earth Sciences Division, Lawrence Berkeley Laboratory.

Pruess K., Narasimhan T. N. (1982) *On fluid reserves and the production of superheated steam from fractured, vapor-dominated geothermal reservoirs,* J. Geophys. Res. 87 (1982) 9329–9339.

Pruess K., Narasimhan T. N. (1985) *A practical method for modeling fluid and heat flow in fractured porous media,* Society of Petroleum Engineers Journal 25, Number 1 (Feb 1985) 14–26.

Straus J. M., Schubert G. (1981) *One-dimensional model of vapor-dominated geothermal systems,* J. Geophys. Res. 86 (1981) 9433–9438.

Truesdell A. H., White D. E. (1973) *Production of superheated steam from vapor-dominated geothermal reservoirs,* Geothermics 2 (1973) 154–173.

White D. E., Muffler J. P., Truesdell A. H. (1971) *Vapor-Dominated hydrothermal systems compared with hot-water systems,* Economic Geology 66 (1971) 75–97.

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