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IMPROVED ENERGY RECOVERY FROM GEOTHERMAL RESERVOIRS

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Marcelo Lippmann, and Sveinbjörn Björnsson

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IMPROVED ENERGY RECOVERY FROM GEOTHERMAL RESERVOIRS

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Abstract

Numerical simulation methods are used to study how the exploitation of different horizons affects the behavior of a liquid-dominated geothermal reservoir. Our reservoir model is a schematic representation of the Olkaria field in Kenya. The model consists of a two-phase vapor-dominated zone overlying the main liquid dominated reservoir. Four different cases were studied, with fluid produced from: 1) the vapor zone only, 2) the liquid zone only, 3) both zones, and 4) both zones, but assuming lower values for vertical permeability and porosity. The results indicate that production from the shallow two-phase zone, although resulting in higher enthalpy fluids, may not be advantageous in the long run. Shallow production gives rise to a rather localized depletion of the reservoir, whereas production from deeper horizons may yield a more uniform depletion process, if vertical permeability is sufficiently large. The exploitation from deeper zones causes boiling and subsequent upflow of steam which condenses at shallow depths. This tends to make temperatures and pressures more uniform throughout the reservoir, resulting in maximum energy recovery.

Brief consideration is given to the possibility of achieving similar improvements in energy recovery from vapor-dominated reservoirs by producing from deeper horizons. This appears unlikely, but cannot be completely ruled out due to uncertainties about the characteristics of vapor-dominated systems at depth.

1. Introduction

In the development of a geothermal resource, an appropriate production strategy must be selected. This includes deciding upon the optimal well spacing and depths of completion. In many cases these decisions are based solely on achievable levels of power production, without giving due consideration to ultimate energy recovery. Thus, the production

wells are often located very close to each other and the completion depth is determined based on available exploration data. This may lead to short lived production wells and a low recovery ratio for the geothermal resource. Selection of an exploitation strategy should be based on appropriate reservoir engineering calculations that will result in an optimum balance between energy recovery and investment costs. Calculations aiming at an optimization of field development were carried out by Morris and Campbell¹ for the East Mesa geothermal field in the Imperial Valley, California.

The economic value of a geothermal well depends not only on its deliverability, as in the case of an oil well, but also on the enthalpy of the produced fluids. If there is a two-phase zone or a vapor zone present in the field (e.g., Baca, USA; Olkaria, Kenya; Broadlands, New Zealand), there is an incentive to produce from them, rather than from deeper liquid reservoirs, because fluids of higher enthalpy can be obtained. The short-term benefits are obvious, but in the long run, a lower energy recovery ratio from the field may result.

In the present work, the behavior of a liquid-dominated geothermal reservoir in response to production from different horizons is studied using numerical simulation methods. We use the Olkaria geothermal field in Kenya as an example where a two-phase vapor-dominated zone overlies the main liquid-dominated reservoir. One of the important questions arising in the development of the Olkaria field is from which zone is it most beneficial to produce. The present paper is the first attempt to answer that question. We also briefly consider the possibility of improving energy recovery from vapor-dominated reservoirs by tapping deeper horizons.

2. Liquid-Dominated Reservoirs

As an example of liquid-dominated geothermal reservoirs, we chose to simulate the Olkaria geothermal reservoir in Kenya. The present plans at Olkaria call for the construction of a 45 MW_e power

plant. The data used in the following discussion have been reported by Noble and Ojiambo, U.N. Feasibility Reports, McNitt, and Björnsson.^{2,3,4,5}

3. Olkaria-Reservoir Model

Surface exploration of the Olkaria geothermal field started in 1956 and exploratory drilling in 1973; presently approximately 20 production wells have been drilled at the site. Resistivity surveys have indicated the presence of a large resource extending over an area of approximately 100 km². The wells are located within the lowest resistivity zone (<20 ohm-m), which covers an area of 12 km². The wells range in depth from approximately 1000-1700 m. The following reservoir model has been developed based on well data⁵:

At 700-800 m depth, below the caprock, the wells have penetrated a 50-150 m thick vapor-dominated zone. The vapor zone is believed to contain 10-25% by volume immobile residual water. A thick water-dominated reservoir underlies the vapor zone. Seismic data have indicated that the basement depth is approximately 3600 m indicating that the thickness of the water zone is of the order of 2700 meters. The water reservoir is believed to be in two-phase conditions with steam saturation in the range of 10-25% by volume.

A pressure of 35 bars has been measured in the vapor zone, corresponding to a temperature of approximately 240°C. The pressure in the water zone is believed to follow the boiling point to depth curve.⁶ This would indicate that the temperature of the basement rocks exceeds 360°C.

The reservoir rocks consist of acid lavas, tuffs, and agglomerates. The lava flows are typically on the order of 50 m thick. Well tests performed on the wells have indicated an average reservoir permeability of 10-20 md. This type of testing, in general, will reflect horizontal permeability of the reservoir rocks.

At Olkaria, if the fluid is produced mainly from contact zones between lava flows, the vertical permeability may be significantly lower than the horizontal permeability (10-20 md). Assessment of the producibility of the Olkaria reservoir must therefore include a thorough sensitivity analysis of the effects of anisotropic permeabilities.

4. Numerical Approach

The numerical simulations were carried out using the code SHAFT79.⁷ The reservoir model used in the numerical simulations is shown in Figure 1. The vapor zone is assumed to be 150 m thick, and underlain by a 2700 m thick liquid-dominated zone. The caprock and bedrock are assumed to be closed to mass and heat flow.

The conductive heat flow through the basement and caprock, and the relatively small fluid discharge at the surface are neglected in the model. Due to the large production rate assumed in the calculations, these approximations should not signifi-

cantly affect the computed response of the reservoir to exploitation.

The mesh used in the study consists of a total of 59 disk-shaped elements, varying in thickness from 10-200 m. The elements form a one-dimensional vertical column with the top 15 elements (a total of 150 meters) representing the initial vapor zone. The remaining 44 elements represent the initial water zone, with fine (10 meter thick) elements close to the boundary between the vapor and the water zones, and thicker elements at greater depths.

The reservoir is assumed to cover a 12 km² area, which corresponds to that of the largest resistivity low at Olkaria. The present reservoir model ignores horizontal variations in reservoir properties and conditions. The four cases studied are shown schematically in Figure 1. In Case 1, it is assumed that the wells produce solely from the vapor zone. Case 2 studies production from the water zone only. In Cases 3 and 4, the fluids are produced from both the vapor and water zones. The thickness of the production interval used in each case is shown in Figure 1.

The reservoir parameters used in the study are given in Table 1. It should be noted that in Case 4 lower values were used for reservoir permeability (2 md) and porosity (5%). The initial pressure, temperature and vapor saturation profiles are shown in Figure 2. We neglect the small amount of steam that may be present in the water zone; it would have little impact on the simulated reservoir behavior. Below the vapor zone, the pressure and temperature follow the saturation curve.

The relative permeability functions used were the 4th-order Corey Equations:

$$k_{rl} = \begin{cases} [S^*]^4 & S < 1 - S_{rl} \\ 0 & S \geq 1 - S_{rl} \end{cases} \quad (1)$$

$$k_{rs} = \begin{cases} [1-S^*]^2[1-(S^*)^2] & S > S_{rs} \\ 0 & S \leq S_{rs} \end{cases} \quad (2)$$

$$\text{where } S^* = \frac{1 - S_{rl} - S}{1 - S_{rl} - S_{rs}}$$

All parameters are defined in the Nomenclature. In this study, the specific relative permeability functions used are not of primary importance as the basic features of reservoir behavior are the same regardless of the assumed relative permeability curves.

The production strategy employed in the modeling studies was to produce the required steam supply for a 45 MW_e power plant. This requirement leads to

variable mass flowrate with time. When the fluid is produced from the water zone, in comparison with production from the vapor zone, a considerably larger mass of fluid is needed to obtain the required steam supply (theoretically 120 kg/s of steam are needed for a 45 MW_e power plant). In order to satisfy the constant steam requirement criterion, the steam fraction in the separators must be calculated and the total flowrate at each time step be adjusted accordingly. The following equations were incorporated into SHAFT79 to carry out the calculations:

$$H_w = S_{sv} H_{sv} + (1-S_q) H_{sl} \quad (3)$$

$$Q_t = Q_s / S_q \quad (4)$$

Equation 3 approximates the two-phase flow from the well bottom to the separators as an iso-enthalpic expansion. It was used to calculate the steam quality in the separators (S_q). The enthalpy values used in equation 3 were calculated based on a 8-bar separator pressure. Saturated steam enthalpy does not vary much with pressure, so that different separator pressure values will not significantly alter the results. The total mass flow rate (Q_t) was calculated using equation 4.

In all of the cases studied, we assume that the required steam supply is produced uniformly over the production interval. In other words, more mass of fluid is produced from a water-dominated element than from a vapor-dominated element. The amount of steam to be extracted from an element is proportional to the size (i.e., thickness) of the element.

5. Simulation Results

Case 1: Production From Vapor Zone Only

In this case, the fluid was produced solely from the vapor zone (see Figure 1). Figure 3 shows a plot of pressure versus depth at different times for this case. The inset in Figure 3 illustrates the production interval. The figure shows that during the 18.7 years of simulation, the pressure changes quite slowly in the system, but rather more rapidly in the vapor zone than in the underlying water reservoir. This is due to the more intense boiling in the vapor zone than in the water reservoir. The pressure in the water zone changes only because the initial pressure is somewhat higher than the saturation pressure.

Figure 4 shows vapor saturation profiles at different times during the simulation. The boiling front advances downwards with time, reaching 1000 meters depth below the caprock at the end of the simulation (18.7 years). The vapor saturation in the upper portion of the vapor zone increases quite rapidly with time, due to boiling. In the lower portion of the vapor zone, the vapor saturation actually decreases at early times due to upflow of liquid water, but then the saturation gradually starts building up again. The upflow of water occurs because of the extensive boiling and associated temperature and pressure decline in the vapor zone, resulting in pressure gradients that

exceed the hydrostatic pressure gradient for liquid water. Later on, however, the water upflow ceases because the water mobility at the top of the water reservoir is steadily decreasing, due to the increasing vapor saturation (relative permeability effects).

The total mass production rate is shown in Figure 5. The fluid is produced uniformly from the top 15 elements in the mesh, representing the vapor zone. Since all of the elements are equal in size, each produced 8.0 kg/s of steam. Figure 5 shows that initially 120 kg/s of steam-water mixture is produced, but rapidly the rate increases to 245 kg/s. The variations in the flowrate occur because of the upflow of water into the vapor zone, as shown in Figure 4 by the decrease in vapor saturation. During the simulation, the vapor elements close to the initial vapor-water interface decrease in vapor saturation. When saturation. When the liquid saturation exceeds the immobile liquid saturation (in our case $S_{rg} = .35$), a mixture of liquid and vapor is produced. At that time, the mass of fluid produced must be increased to satisfy the constraint of a constant steam withdrawal rate. As shown in Figure 5, the total flowrate declines again after 6 years because of an increasing vapor saturation in the steam elements.

Due to large computing costs, the simulations of Case 1 were terminated after 18.7 years. At this time, the top elements in the vapor zone have saturations close to 1.0 and the imminent phase transitions, with their associated large changes in pressures and flow rates, necessitate small time steps. In Case 1, boiling is occurring only at the top of the reservoir (the vapor zone and the upper parts of the water zone) as the temperature changes in Figure 6 clearly show. Consequently the vapor elements increase rapidly in vapor saturation. Previous experience with this type of reservoir behavior indicates that very soon after the vapor elements make a transition to single phase conditions, the pressure in the vapor zone will start to fall drastically.^{8,9} We believe that the pressure will fall so rapidly in the vapor zone that production could not be sustained for more than 25 years.

Case 2: Production From the Water Zone Only

In this case the fluids are produced from the water zone underlying the vapor cap (see Figure 1). We assume that the vapor zone and the top 100 meters of the water zone are cased off, however, the wells are open to a 500 meter thick interval in the water zone. This case gives rise to a rather remarkable and interesting depletion pattern, as will be discussed below.

Figure 7 shows the pressure variations in the reservoir at different times during the simulation. The initial pressure distribution is given for reference purposes. The figure shows that at early times the pressure decreases rather evenly in the water zone, but actually increases in the vapor zone. In the upper portion of the water zone, the pressure decreases along with the temperature due to boiling, but in the lower portions of the water zone, the pressure decrease is due to a steady upflow of water. In the vapor zone, however, pressures and tempera-

tures increase because vapor, which has been mobilized by the boiling process, flows up from depth and condenses near the top. The upflow of vapor replenishes mass reserves near the production horizons, and gives rise to a very long reservoir life. The pressure gradients in the upper part of the system are lower than hydrostatic, thereby preventing upward flow of water. The pressure gradients are considerably higher than vaporstatic, however, which permits mobile vapor to flow upward. This results in condensation in the upper part of the water zone as well as in the vapor zone.

At later times, the boiling spreads down to the deeper portions of the reservoir, creating upflow of vapor and condensation in the upper part of the water zone as well as in the vapor zone. These processes eventually give rise to almost isothermal conditions and uniform boiling throughout the entire reservoir after 200 years of simulation. At that time the pressure has increased by 50 bars in the vapor zone and 35 bars in the production zone; in the liquid zone (2000 m below the caprock) the pressure has decreased by 50 bars (Figure 8).

The saturation profiles are shown for different times in Figure 9. The boiling front advances rapidly downwards, reaching the bottom of the reservoir after less than 50 years. The vapor saturation in the vapor zone decreases during the first 100 years of simulation due to the inflow and condensation of steam from depth. After 50 years, the boiling is most pronounced near the bottom of the reservoir due to the large upflow of water and steam and the effect of the impermeable boundary at the bottom of the reservoir. This gives rise to relatively higher saturations at the bottom of the reservoir at large times, eventually leading to single-phase vapor conditions after little over 100 years. The saturation profiles show clearly the nearly uniform depletion process that takes place in the reservoir, giving rise to a very long productive life of the reservoir.⁸

The processes of production-induced boiling, upflow and condensation of steam, and subsequent increase in temperature and pressure at shallower depths which were noted in the present simulation actually have been observed in some water-dominated geothermal fields. Henley¹⁰ and Allis¹¹ report increases in the flowrates and temperatures of surface manifestations at the Wairakei and Tauhara geothermal fields after exploitation started. Similar effects have been observed at the Tongonan geothermal field in the Philippines (V. Steffánsson, private communication).

The total fluid production is shown as a function of time in Figure 10. Initially large amounts of liquid water are produced due to the low steam quality in the separators. After about 5 years the vapor saturation in the production nodes has exceeded the immobile vapor saturation (in our case, $S_{rg}=0.05$), and from then on a mixture of vapor and liquid water is produced. As the vapor saturation in the production nodes increases, the vapor quality in the separators increases and eventually, after 120 years, only steam is produced. At this time the liquid saturation in the production nodes has fallen below the im-

mobile liquid saturation and the total flowrate produced corresponds to the theoretical steam requirement for a 45 MW_e power plant (120 kg/s).

Case 3: Production From Both Vapor and Liquid Zones

Figure 1 shows schematically the production interval used in Case 3. It is assumed that the wells are drilled to a total depth of 1300 m. The perforated interval is 550 m long and the wells are open both in the initial vapor zone as well as in the water zone.

During the simulation, the pressure and saturation changes with time were very similar to those obtained in Case 2. Upflow and condensation of steam in the upper portions of the reservoir gave rise to a similar uniform depletion pattern as noted in Case 2. The reasons for this similarity are obvious; the high vapor saturation in the vapor zone and the long production interval (550 m) lead to low production rates from the vapor zone. This in turn causes condensation to control the pressure changes in the vapor zone and the upper portion of the water zone. Comparison of this case with Case 1 illustrates clearly that high flowrates from the vapor zone will decrease the productive life of the reservoir considerably, whereas low to moderate production rates will enable production of high enthalpy fluids, and also result in a longer reservoir life.

Comparison of Cases 2 and 3 show that in Case 3 the reservoir pressures are higher at all times. The reason for this is obvious when one compares the total mass withdrawn in the two cases (Figures 10 and 11). In Case 3, the fluids are produced from both the vapor and the water zones, resulting in higher average flowing enthalpy of the liquid-vapor mixture. This in turn, when compared with Case 2, results in a smaller fluid mass to be extracted from the reservoir at any given time.

Case 4: Production From Both the Vapor and the Water Zone, Assuming Low Vertical Permeability

The final case studied differs from Case 3 only in that lower reservoir permeability and porosity values were used in the simulation (see Table 1). In this case, the permeability and porosity were reduced to 2 md and 5%, respectively. The permeability of the Olkaria reservoir inferred from well tests is 10-20 md. This value essentially represents the average horizontal permeability of the reservoir. The geological characteristics of the Olkaria reservoir seem to indicate, however, that the vertical permeability may be considerably lower. Case 4 represents an attempt to study the sensitivity of our results to changes in vertical permeability. The average porosity of the Olkaria reservoir has been estimated as 5-10%; in this case the lower limit of 5% is used. This case should represent a more pessimistic outlook on the behavior of the Olkaria geothermal field under exploitation.

The pressure profiles at different times are shown in Figure 12. Although the total simulation time only slightly exceeded 70 years, we feel that the general depletion trend of the reservoir can be clearly seen. Figure 12 shows that the

pressure decreases rather rapidly in the production region, but only slightly in the deeper portions of the reservoir. This shows that the boiling is confined to a rather small region around the production interval, due to the low permeability of the reservoir.

The vapor saturation profiles given in Figure 13 similarly show the slow advance of the boiling front during exploitation. A comparison with Case 3 shows that in Case 4, after 70 years, the boiling front has advanced only to a depth of 1600 meters below the caprock in this case, whereas in Case 3, the boiling front had advanced to the bottom of the reservoir (2850 meters below the caprock) after less than 50 years. Also, it is of importance to note that the vapor saturation in the vapor zone always increases with time. This illustrates the effect of the lower permeability allowing less upflow of vapor and consequently less condensation in the vapor zone.

The total flow rate (Q_t), as shown in Figure 14, is very similar to that of Case 3. However, at later times it is smaller due to the higher vapor saturation in the production nodes.

The results from this case show clearly that the vertical permeability is a very important factor in the determination of the longevity of a liquid-dominated reservoir.

6. Single-Phase Liquid-Dominated Reservoirs

The general results shown above for the Olkaria-type geothermal reservoir should also be applicable to liquid-dominated reservoirs without an initial steam cap (e.g. Salton Sea, USA; Cerro Prieto, Mexico; Krafla, Iceland). If the initial reservoir pressure is above the saturation pressure corresponding to the reservoir temperature, soon after exploitation starts the pressure will drop to the saturation pressure.⁹ After that, a two-phase zone will develop in the upper portion of the reservoir and conditions similar to those presently found at Olkaria will result. Production-induced boiling has recently been observed at the Svartsengi geothermal field in Iceland (J. Eliasson, private communication). Although the aquifer at Svartsengi contained initially only single-phase liquid water, recently a two-phase zone has been formed at the top of the aquifer. Note that if the colder water recharge is significant, the two-phase zone could be restricted to the near-well regions, as in Cerro Prieto.¹²

7. Vapor-Dominated Reservoirs

Let us now consider the question whether production from deeper horizons in vapor-dominated reservoirs could give rise to similar effects as those discussed above. Two conditions must be met in order that production from depth will cause increasing upflow of steam, which would replenish mass reserves in shallower horizons, and give rise to temperature and pressure increases due to condensation: (1) initially relative permeability for steam must be significantly less than 1 at depth, so that production-induced increases in vapor saturation will result in

higher steam mobility, and (2) vertical pressure gradients at depth must be substantially larger than vaporstatic, preferably approaching hydrostatic, so that mobile steam will actually be driven upward in significant amounts.

It is not known whether either of these conditions exist in vapor-dominated reservoirs. Both conditions could be met in a "deep water table" which for a long time has been hypothesized to underlie vapor-dominated reservoirs, but has never been unambiguously identified.^{13, 14} Below a water table, pressure gradients would have to be close to hydrostatic, and vapor saturation presumably would be small. At Larderello, Italy, there may be some evidence that vertical pressure gradients at depth significantly exceed vaporstatic values. However, published data for The Geysers, USA, do not give any indication of large vertical pressure gradients at depth. Therefore, upflow of steam appears to be limited by pressure gradients so that any increase in mobility would only have small effects. Moreover, it appears doubtful whether the effective mobility for vertical steam flow could be significantly increased by production-induced rise in vapor saturation. Recent work on vapor-dominated reservoirs, which has specifically addressed the effects arising from the fractured nature of these systems, indicates that the vertical flow of steam may be essentially unaffected by relative permeability.¹⁵ The reason for this is that steam moves along vertical fractures which contain little or no water even in the pre-exploitation state, so that the relative permeability to steam is 1. Production from depth would increase vapor saturation and mobility in the rock matrix, but this may have a negligible effect on the vertical flow because the matrix permeability is much smaller than the fracture permeability.

In summary, we consider it unlikely that conditions in vapor-dominated reservoir are such that depletion at great depth could significantly replenish the fluid and heat reserves at shallow depth. But given the uncertainties about the characteristics of vapor-dominated reservoirs at depth, it may still be worth trying to tap deep horizons in order to improve energy recovery.

8. CONCLUSIONS

We have studied the behavior of a liquid-dominated geothermal reservoir (Olkaria, Kenya) with an overlying two-phase zone when produced from various reservoir horizons. Our studies concluded that:

- 1) Production from depth can give rise to an optimal energy recovery of the reservoir. If the permeability is adequate, a remarkably uniform depletion process may result, in which a counterflow of steam and liquid water results initially in the mining of heat and mass from lower portions of the reservoir, while pressures are stable, or even increase, in its shallower portions. Later, uniform boiling will occur everywhere in the reservoir. Field data from Wairakei, New Zealand, have verified some of the mechanisms operative in this process.

- 2) Extensive production from the vapor zone may be advantageous in the short run, but in the long run, localized boiling will enhance single-phase vapor conditions in the production regions and will result in a short productive life for the reservoir.
- 3) The uniform boiling process described in (1) is very sensitive to the reservoir vertical permeability. If the vertical permeability is very low, upflow of significant mass of steam will not occur, and consequently the pressure increase due to steam condensation in shallow regions of the reservoir will not result.
- 4) The results discussed above should be applicable to other liquid-dominated reservoirs, regardless whether a shallow two-phase zone is present initially or not.
- 5) It is questionable whether production from depth will enhance production in shallow regions of vapor-dominated reservoirs. Due to the uncertainties regarding the characteristics of those systems at depth, such a possibility can not be ruled out at present.

In assessing the results from the present study, one must bear in mind that a simple reservoir model was used, which is not expected to quantitatively account for field behavior. Future investigations should employ a more detailed model to determine the sensitivity of the results to reservoir geometry, horizontal and vertical variations in reservoir properties, and different relative permeability curves.

Nomenclature

- k_{rw} = Relative permeability of liquid phase
- k_{rl} = Relative permeability of vapor phase
- S = Vapor saturation
- S_{rl} = Residual (immobile) liquid saturation
- S_{rs} = Residual (immobile) vapor saturation
- H_w = Flowing enthalpy (J/kg)
- H_{sl} = Enthalpy of saturated liquid in flash tank (J/kg)
- H_{sv} = Enthalpy of saturated steam in flash tank (J/kg)
- S_q = Steam quality in flash tank
- Q_t = Total flow rate (kg/s)
- Q_s = Theoretical steam required for the geothermal power plant (kg/s)
- k = Absolute permeability (md)
- ϕ = Porosity

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References

1. Morris, C.W., and Campbell, D.A.: "Geothermal Reservoir Energy Recovery: A Three-Dimensional Simulation Study of the East Mesa Field", paper SPE 8229 presented at the SPE 54th Annual Fall Technical Conference, Las Vegas, Nevada, September 23-26, 1979.
2. Noble, J.W., and Ojiambo, S.B.: "Geothermal Exploration in Kenya", Proc. Second United Nations Symposium on the Development and Use of Geothermal Resources, San Francisco, CA (1976), 1, 189-204.
3. U.N./Kenya Government: "Feasibility Report for the Olkaria Geothermal Project," SWECO, and VIRKIR, v. 1 and 2, 1976.
4. McNitt, J.R.: "Origin of Steam in Geothermal Reservoirs", paper SPE 6764 presented at the SPE 52nd Annual Fall Technical Conference, Denver, Colorado, October 9-12, 1977.
5. Björnsson, S.: "Estimations of the Reservoir Potential of the Olkaria Geothermal Field, Kenya", Presented at the Nordic Symposium on Geothermal Energy, May 29-31, 1978.
6. Truesdell, A.H. and White, D.E.: "Production of Superheated Steam from Vapor-Dominated Geothermal Reservoirs," Geothermics, 2, 154-173 (1973).
7. Pruess, K., and Schroeder, R. C.: "SHAFT79 User's Manual," LBL Report 10861, Lawrence Berkeley Laboratory, Berkeley, CA (March, 1980).
8. Pruess, K., Bödvarsson, G.S., Schroeder, R.C., Witherspoon, P.A., Marconcini, R., Neri, G., and Ruffilli, C.: "Simulations of the Depletion of Two-Phase Geothermal Reservoirs", paper SPE 8266 presented at the SPE 54th Annual Technical Conference, Las Vegas, Nevada, September 23-26, 1979.
9. Bödvarsson, G.S., Vonder Haar, S.P., Wilt, M.J., and Tsang, C.F.: "Preliminary Estimation of the Reservoir Capacity and Longevity of the Baca Geothermal Field, New Mexico," paper SPE 9273 presented at the SPE 55th Annual Fall Technical Conference, Dallas, Texas, September 21-24, 1980.
10. Henley, R.W.: "Evolution of the Tauhara Geothermal System," Proc. New Zealand Geothermal Workshop, Univ. Auckland, N.Z. (1979), 1, 7-9.

11. Allis, R.G.: "Changes in Heat Flow Associated with Exploitation of the Wairakei Geothermal Field," Proc. New Zealand Geothermal Workshop, Univ. Auckland, N.Z. (1979), 1, 11-13.
12. Grant, M.A., Truesdell, A.H., Mañón, A., C.J. Janik, J. Fausto, M.E. Jiménez, and J. Sánchez R.: "Production Induced Boiling and Cold Water Entry in the Cerro Prieto Geothermal Reservoir Indicated by Chemical and Physical Measurements," Abstracts, Third Symposium on the Cerro Prieto Geothermal Field, San Francisco, CA, March 24-26, 1981, LBL Report 11967, Lawrence Berkeley Laboratory, Berkeley, CA, 23.
13. White, D. E., Muffler, L. J. P., and Truesdell, A. H.: "Vapor-Dominated Hydrothermal Systems Compared with Hot-Water Systems," Econ. Geol., 66, 75-97 (1971).
14. Weres, O., Tsao, K., and Wood, B.: "Resource, Technology, and Environment at The Geysers," Lawrence Berkeley Laboratory, LBL Report 5231, Berkeley, CA, (July 1977).
15. Pruess, K., and Narasimhan, T. N.: "On Fluid Reserves and the Production of Superheated Steam from Fractured, Vapor-Dominated Geothermal Reservoirs," submitted to Econ. Geol. (1981).

TABLE 1
Parameters Used in the Study

Cases 1, 2, and 3

Absolute permeability:	20 md
Porosity:	10%
Heat capacity of rocks:	1000 J/kg ^{°C}
Density of rocks:	2650 kg/m ³
Thermal conductivity:	2.0 J/m·s·°C
Relative permeabilities:	Corey Equations (see equations 1 and 2)
Residual (immobile) liquid saturation:	0.35
Residual (immobile) vapor saturation:	0.05

Case 4

Absolute Permeability:	2 md
Porosity:	5%

All other parameters
same as above

FIGURE CAPTIONS

- Fig. 1 - A schematic reservoir model of the Olkaria geothermal field.
- Fig. 2 - Initial reservoir conditions.
- Fig. 3 - Pressure transients for Case 1.
- Fig. 4 - Changes in vapor saturation due to production from vapor zone (Case 1).
- Fig. 5 - Changes in mass flowrate during production from vapor zone (Case 1).
- Fig. 6 - Temperature changes due to production from vapor zone (Case 1).
- Fig. 7 - Pressure changes due to production from liquid zone (Case 2).
- Fig. 8 - Pressure changes with time at three different parts of the reservoir (Case 2).
- Fig. 9 - Vapor saturation changes due to production from liquid zone (Case 2).
- Fig. 10 - Flowrate changes due to production from liquid zone (Case 2).
- Fig. 11 - Flowrate changes during production from both vapor and liquid zones (Case 3).
- Fig. 12 - Pressure changes during simulation of Case 4.
- Fig. 13 - Vapor saturation changes during simulation of Case 4.
- Fig. 14 - Flowrate changes during simulation of Case 4.

OLKARIA - basic model

XBL 814-2914

Figure 1

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Figure 2

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Figure 3

Figure 4

XBL 814-2917

Figure 5

XBL 814-2918

Figure 6

Figure 7

Figure 8

XBL 814 - 2920

Figure 9

XBL 814 - 2921

Figure 10

XBL 814-2924

Figure 11

XBL 814-2925

Figure 12

XBL 814-2926

Figure 13

XBL 814 - 2927

Figure 14

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