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THE SENSITIVITY OF GEOTHERMAL RESERVOIR BEHAVIOR TO RELATIVE PERMEABILITY PARAMETERS

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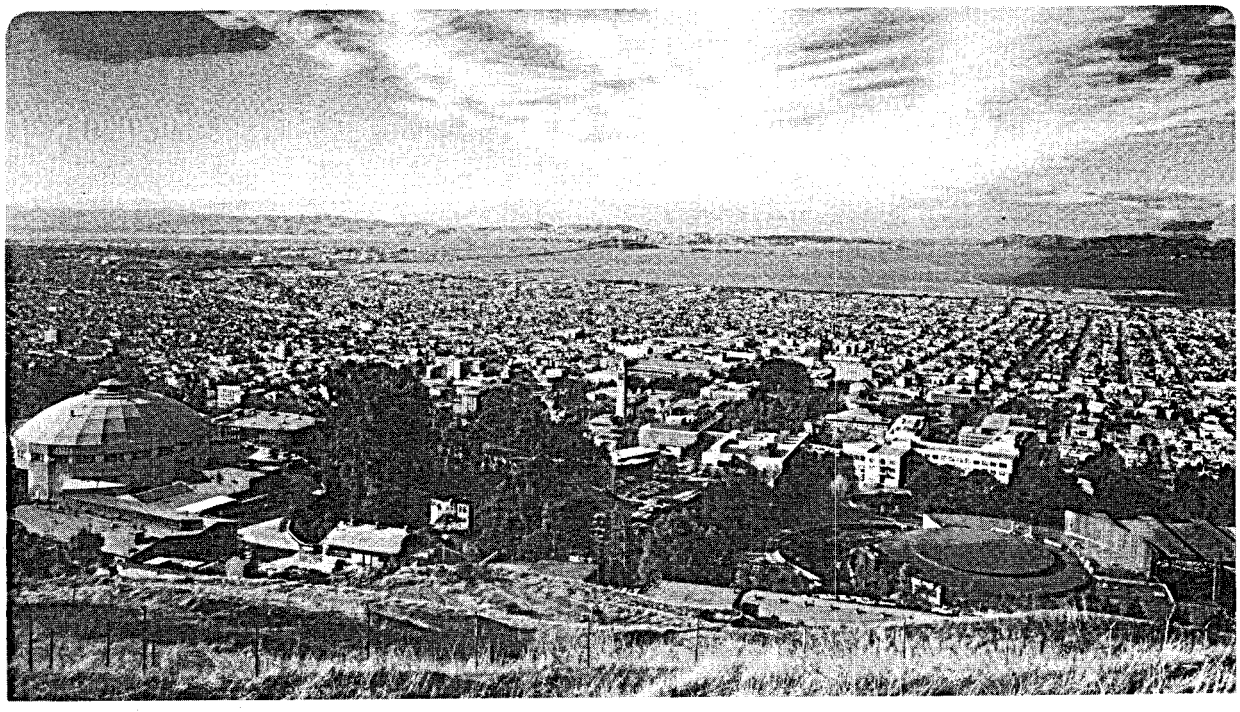

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THE SENSITIVITY OF GEOTHERMAL RESERVOIR BEHAVIOR TO RELATIVE PERMEABILITY PARAMETERS

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INTRODUCTION

In two-phase flow through a porous material, the movement of each individual phase is retarded by the presence of the other; the degree of interference depending, among other things, on the volumetric proportion of the two phases. This phenomenon is expressed mathematically by the saturation dependent relative permeability functions k_{rl} and k_{rv}, for the liquid and vapor phases respectively. Because the two phases move differentially (weighted by the relative permeability functions) the mixture behaves like a fluid with a saturation-dependent "effective" or total kinematic viscosity ν_t given by:

$$\frac{1}{\nu_t} = \frac{k_{rl}}{\nu_l} + \frac{k_{rv}}{\nu_v} \qquad [1]$$

where ν_l and ν_v are the kinematic viscosities of the liquid and vapor phases respectively. Similarly, the enthalpy transported by the mixture depends on the relative permeabilitiy functions and is different from the in-place enthalpy. This "flowing" enthalpy h_f is given by:

$$h_f = \nu_t \left[h_l \frac{k_{rl}}{\nu_l} + h_v \frac{k_{rv}}{\nu_v} \right] \qquad [2]$$

where h_l and h_v are the liquid and vapor enthalpies respectively.

The movement of mass and energy in a geothermal reservoir is very strongly influenced by the magnitude of the total kinemati viscosity and the flowing enthalpy, which in turn obviously depend on the nature of the relative permeability functions (equations 1 and 2). Unfortunately the functional forms of k_{rl} and k_{rv} in terms of liquid saturation S_l are not presently known and are very difficult to deduce from laboratory experiments or field data. Various preliminary curves have been assumed and used by a number of modelers.

In the present work three problems are considered; (1) the sensitivity of ν_t and h_f to variations in the relative permeability functions; (2) the determination of ν_t and h_f from well-test data, following which a method of is suggested to use these results together with theoretical plots of k_{rl} and k_{rv} versus h_f to deduce the general shape of the relative permeability functions is suggested; and (3) the effect of the

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relative permeability functions on the pressure decline and flowing enthalpy build-up during a constant rate production test. It is shown that the characteristic rise in the flowing enthalpy from its initial value to a stable value after a moderate time is strongly influenced by the dependence of h_f on S_l (and hence k_{rl} and k_{rv} on S_l).

PREVIOUS WORK

Various investigators have studied the relative permeability functions. Experimental work to determine the relative permeability curves has been reported, among others, by Corey (1954), Chen et al., (1978), and Counsil and Ramey (1979). Grant (1977) and Horne and Ramey (1978) used flowrate and enthalpy data from the Wairakei geothermal field in New Zealand to obtain information about the relative permeabilty parameters. Numerical modeling studies of the sensitivity of reservoir behavior to relative permeability curves have been reported by Jonsson (1978), Sun and Ershaghi (1979) and Bodvarsson et al., (1980). Finally, Sorey et al., (1980) illustrated effects of the relative permeabilities on the pressure drop and enthalpy variations during production from a single well by considering relative permeability curves suggested by Corey (1954) and Grant (1977).

SENSITIVITY STUDY

Various relative permeability curves for steam and liquid water have been proposed in the literature (Corey, 1954; Chen et al., 1978; Horne and Ramey, 1978; and Counsil and Ramey, 1979). However, since the suggested curves vary widely, the choice of relative permeability curves to be used in studies of geothermal systems is rather arbitrary. Therefore at this stage it is important to determine which characteristics of the relative permeability curves are significant.

In the present study attention is mainly confined to either Corey type curves or straight line curves (see Figure 1). The most important characteristics of these curves are the "cutoffs" where steam or water becomes either fully mobile or immobile (four possible cutoffs).

We have conducted a sensitivity study to determine the relative importance of each of the cutoffs. The approach used is quite simple; for horizontal flow (no gravity) the relative permeability curves influence reservoir behavior only through the flowing enthalpy, h_f, and the total kinematic viscosity, ν_t. Therefore, by observing the effect of the individual cutoffs on these quantities, their relative importance can be determined. In this sensitivity study, five straight line functions are considered: four possible curves each having one 30% cutoff, and what we call the "X" curves, which correspond to the case without any cutoffs (broken lines in Figure 1).

Figure 2 shows the effect of the cutoffs on the flowing enthalpy. For comparison the "X" relative permeability curve is shown as the thick solid line. The figure shows that when considering flowing enthalpy, the immobile liquid cutoff is much more important than the other cutoffs.

Figure 3 shows the effect of the cutoffs on the total kinematic viscosity (ν_t). Again results based on the "X" relative permeability curves are included for comparison. In this case, both of the liquid water cutoffs are considerably more important than the vapor cutoffs. However, in terms of the percentage deviation from the "X" curve (the thick solid line), the immobile liquid water cutoff is more significant than the fully mobile liquid water cutoff. The vapor cutoffs again are not very important. Similar conclusions regarding the importance of the cutoffs are obtained by Sun and Ershagi (1979), in considering the heat output from a one-dimensional system.

WELL TEST DATA

During well tests in a two-phase reservoir, the downhole pressure follows a decline curve similar to that shown in Figure 4. The exact shape of the curve varies with reservoir conditions but in general does not follow a straight line (Theis curve) because the mobility changes as the saturation changes near the well. Nevertheless, the slope at any point on the decline curve can be used to calculate the mobility at the corresponding pressure using the formula:

$$\frac{kH}{\nu_t} = \frac{2.303Q}{4\pi m} \qquad [3]$$

(See Garg, 1978; Sorey et al., 1989; or O'Sullivan, 1980.) The flowing enthalpy of the produced fluid typically follows a curve like that shown in Figure 5, rising from an initial value to a higher stable value after a moderate time. Simultaneous measurements of pressure and flowing enthalpy thus enable the determination of ν_t and h_f provided kH is known (e.g., from an injection test).

Using equations (1) and (2), k_{rv} and k_{rl} can then be calculated. By making these calculations for a number of values of flowing enthalpy (either at different times during the test or by using different production rates), plots of k_{rv} and k_{rl} versus h_f can be obtained. However, because the corresponding liquid saturation S_l is not known and cannot be measured satisfactorily, the relative permeability curves cannot be obtained in terms of the saturation.

RELATIVE PERMEABILITIES VERSUS FLOWING ENTHALPY

Although conventional relative permeability curves cannot be obtained from field data, the plots of k_{rl} and k_{rv} versus

h_f are useful. Theoretical plots of this type for the "X" curves and Corey curves (Figure 1) are shown in Figures 6 and 7.

At present the Corey relative permeability curves are most widely used in reservoir numerical modeling. The curves, illustrated in Figure 1, indicate that under two-phase conditions, where both phases are mobile, the mobility of each phase is severely retarded by the presence of the other. The sum of the individual relative permeabilities never reaches unity, except where one of the fluids is immobile. The other curves shown in Figure 1 are the "X" relative permeability curves. For these curves, the mobility of each phase is a linear function of the saturation, and no cutoffs are present. The "X" curves represent the other extreme; that is, the phases are independent of each other and their mobilities are only a function of their volume fraction. Thus these relative permeabilities represent the likely extremes of what the real relative permeability functions may be.

Figure 6 shows the flowing enthalpy as a function of the liquid relative permeability for the Corey and "X" curves. The figure shows that although the two curves have distinctly different characteristics, they enclose a relatively small zone. It is probable that k_{rl} - h_f values determined from field data will fall within this zone. The vapor relative permeability, when plotted against flowing enthalpy for the Corey and the "X" relative permeability curves (Figure 7), also illustrates the basic difference between the two cases, although the curves are further apart.

The comparison of field results with the curves shown in Figures 6 and 7 should give a clear indication of whether the relative permeability curves at the geothermal field in question more closely resemble the Corey or the "X" relative permeability curves.

THE RISE IN FLOWING ENTHALPY

As explained earlier, the flowing enthalpy in a constant rate well test reaches a stable value after some time. Sorey et al., (1980) studied the rise in flowing enthalpy using an approximate analytical method and found it depended strongly on which relative permeability curves were used. We have used a semi-analytic technique developed by O'Sullivan (1980) to make a more detailed study of the effect of the relative permeability curves on the rise in the flowing enthalpy. In order to explain the main features of the results a brief outline of the basic equations is required.

Basic Equations

Using the transformation $\eta = r/t$ the mass and the energy balance equations for a two-phase system can be written as (O'Sullivan, 1980):

$$\frac{dQ_m}{d\eta} + \frac{\eta^2}{2}\frac{dA_m}{d\eta} = 0 \qquad [4]$$

$$\frac{dQ_e}{d\eta} + \frac{\eta^2}{2}\frac{dA_e}{d\eta} = 0 \qquad [5]$$

In equations (4) and (5), A_m and A_e are the mass and the energy accumulation terms, respectively, where

$$A_m = \phi\rho \qquad [6]$$

$$A_e = (1 - \phi)\rho_r C_r T + \phi(\rho h - p) \qquad [7]$$

The density (ρ) and enthalpy (h) of the fluid mixture are defined as:

$$\rho = \rho_1 S_1 + \rho_v S_v \qquad [8]$$

$$h = (\rho_1 h_1 S_1 + \rho_v h_v S_v)/\rho \qquad [9]$$

The mass (Q_m) and the energy (Q_e) fluxes can be written (ignoring conduction) as:

$$Q_m = T_m \eta \frac{dp}{d\eta} \qquad [10]$$

$$Q_e = h_f Q_m \qquad [11]$$

where the mobility T_m is given by $T_m = k/\nu_t$. Using Q_m, p, and S_1 as independent variables, equations (4), (5), (10), and (11) can be combined to yield:

$$\eta \frac{dS_1}{d\eta} = -\frac{Q_m}{T_m} \frac{Q_m \frac{dh_f}{dp} + \frac{\eta^2}{2}\left[\frac{dA_e}{dp} - h_f \frac{dA_m}{dp}\right]}{Q_m \frac{dh_f}{dS_1} + \frac{\eta^2}{2}\left[\frac{dA_e}{dS_1} - h_f \frac{dA_m}{dS_1}\right]} \qquad [12]$$

Similarly, equations (4) and (5) can be combined to give:

$$Q_m \frac{dh_f}{d\eta} = -\frac{\eta^2}{2}\left[\frac{1}{\eta}\left(\frac{dA_e}{dp} - h_f \frac{dA_m}{dP}\right)\frac{Q_m}{T_m} + \left(\frac{dA_e}{dS_1} - h_f \frac{dA_m}{dS_1}\right)\frac{dS_1}{d\eta}\right] \qquad [13]$$

Equations (12) and (13) will be used as a basis in the following discussion.

Numerical Studies

The phenomenon of stable enthalpy during a constant rate well test has been observed in well data from Wairakei and in numerical simulations of well tests (Sorey et al., 1980; and O'Sullivan, 1980). Analytical verification of a long-time stable flowing enthalpy can be obtained by considering equation (13) in the limit as $\eta \rightarrow 0$ (large times) which yields simply:

$$\frac{dh_f}{d\eta} = 0 \quad \text{or} \quad h_f = \text{constant} \qquad [14]$$

As $\eta \rightarrow 0$ and h_f approaches its constant value, equation (12) can be approximated by:

$$\eta \frac{dS_1}{d\eta} = -\frac{Q_m}{T_m} \frac{\frac{dh_f}{dp}}{\frac{dh_f}{dS_1}} \qquad [15]$$

In the above derivations, the chain rule for partial differentation has been used in the formula:

$$\frac{dh_f}{d\eta} = \left(\frac{\partial h_f}{\partial S_1}\right)_P \frac{dS_1}{d\eta} + \left(\frac{\partial h_f}{\partial p}\right)_{S_1} \frac{dp}{d\eta} \qquad [16]$$

The second term on the right hand side of equation (16) is small and therefore this equation can be used in a discrete form to approximate the rise in flowing enthalpy as follows:

$$\Delta h_f \approx \left(\frac{\partial h_f}{\partial S_1}\right)_P \Delta S_1 \qquad [17]$$

The accuracy of this formula is confirmed by independent calculations. In equation (17), ΔS_1 represents the total change in saturation up to the time when a stable value of the flowing enthalpy is reached. From equation (17) the strong dependence of Δh_f on the relative permeability curves is obvious. However, the saturation change ΔS_1, and therefore also Δh_f, is dependent upon several other factors, including initial conditions (T, S_i), porosity, mass flowrate and total kinematic mobility. The relationships between Δh_f and these parameters must be established before Δh_f can be used to investigate the shape of the relative permeability curves.

Figure 8 shows the rise in flowing enthalpy versus the initial flowing enthalpy for three initial temperatures. The curves in Figure 8 show that the rise of flowing enthalpy is

dependent upon the initial temperature and the initial saturation in the reservoir. The dependence on the initial temperature can be explained by considering equations (12) and (17).

The saturation changes given by equation (12) are more pronounced at lower temperatures (or equivalently at lower pressures), primarily due to the lower total kinematic mobility (T_m) at lower temperatures. Consequently, the flowing enthalpy changes will be larger at lower temperatures (Equation 17). The dependence of Δh_f on the initial saturation can be explained using Figure 9. For the Corey relative permeabilty curves, the change in flowing enthalpy is most pronounced at medium values of saturation and the rise in the flowing enthalpy is therefore largest at those initial saturation values.

The rise in flowing enthalpy also depends on the porosity ϕ and the mass flow rate Q_m. Figure 10 shows a plot similar to that in Figure 8, but a higher porosity is used in the simulation (ϕ = .25). Sorey et al., (1980) developed curves similar to the ones shown in Figures 8 and 10 using an approximate analytical procedure. Their curves in general show a considerably smaller rise in flowing enthalpy than the curves shown in Figure 8 and 10. The difference is due to the approximations involved in deriving the analytical expressions used by Sorey et al.

The relationship between the rise in flowing enthalpy and porosity is shown in Figure 11 for an initial temperature of 250°C and several values of initial saturation. In all of the cases, the lower the porosity, the greater is the rise in flowing enthalpy. In cases of high initial liquid saturation, a linear relationship between the rise in flowing enthalpy and $(1-\phi)/\phi$ is observed for porosity values higher than ϕ = .05. At lower initial liquid saturations non-linear effects are more pronounced. We have confirmed these results by an independent analytical study, but the limited space does not allow elaboration of this work.

The relationship between the mass flowrate and the stable flowing enthalpy is shown in Figure 12. Three curves representing different values of the initial saturation are shown, but in all three cases, the initial temperature of 250°C and a porosity of 0.05 was used. The curves representing high initial saturation (S_i > .80) show an approximately linear relationship between the flowrate and the stable flowing enthalpy, but at lower initial saturations (S_i = .64) a more non-linear behavior is observed. The near linear relationship at high initial liquid saturations can be derived analytically by considering equations (12) and (17). At high initial saturations, the derivatives dh_f/dp and dh_f/dS_l are negligible for the Corey relative permeability curves (see Figure 8), and equation (12) can be written as:

$$\eta \frac{dSe}{d\eta} = - \frac{Q_m}{T_m} \frac{\left(\frac{dA_e}{dp} - h_f \frac{dA_m}{aP}\right)}{\left(\frac{dA_e}{dS_1} - h_f \frac{dA_e}{dS_1}\right)} \qquad [18]$$

The terms in the numerator and denominator of equation (18) are almost constant at higher initial liquid saturations. Consequently,

$$\Delta S_i \ \alpha \ \frac{Q_m}{T_m} \qquad [19]$$

and from equation (17),

$$\Delta h_f \ \alpha \ \frac{Q_m}{T_m} \qquad [20]$$

The slight non-linear effects in the high initial saturation curves shown in Figure 11 are probably due to the fact that T_m decreases slightly with pressure and saturation.

Sorey et al. (1980) observed a near linear relationship between the flowing enthalpy and flowrate from wells in Wairakei, New Zealand. Their use of linear plots, such as the one shown in Figure 11, to obtain the initial reservoir enthalpy for the wells in New Zealand is well justified. However, in the case of a low initial saturation, linear aproximations may be somewhat in error.

In light of the preceeding discussion it is clear that the rise in flowing enthalpy is complicated by various factors such as the porosity, flowrate, and the initial conditions. However if all of these factors are known, the change in saturation may be approximated and the slope of the h_f versus S_1 curves (dh_f/dS_1) determined (equation 17). This in turn will yield information regarding the relatiave permeability parameters.

Calculation have been carried out for several different relative permeability curves. For example, Corey curves and linear curves which produce the same flowing enthalpy but a different gradient for dh_f/dS_1 at a particular initial saturation have been investigated. Work on the problem is continuing.

CONCLUSIONS

The primary results obtained in this study are as follows:

1) The liquid cutoffs are the most important characteristics of the relative permeability curves.
2) The relative permeability parameters can be determined from field data in terms of the flowing enthalpy, and

compared to theoretical curves (e.g., Corey and "X" curves)

3) The rise in flowing enthalpy can give information regarding the relative permeability curves providing parameters such as kH and ϕ are known (e.g., from injection and interference tests).

NOMENCLATURE

C_r = specific heat of rock
h = enthalpy
h_f = flowing enthalpy
h_l = enthalpy of saturated liquid
h_v = enthalpy of saturated vapor
H = reservoir thickness
k = permeability
k_{rl} = relative permeability of liquid phase
k_{rv} = relative permeability of vapor phase
K_m = thermal conductivity
m = slope of semi-log pressure response
P = pressure
Q_m = mass flowrate per unit thickness
r = radial distance
S_l = liquid saturation
S_v = vapor saturation
S_{re} = residual liquid saturation
S_{rv} = residual vapor saturation
t = time
T = temperature
ϕ = porosity
ρ = density of vapor liquid mixture
ρ_l = liquid density
ρ_r = rock density (kg/m^3)
ρ_v = vapor density
ν_e = kinematic viscosity of liquid water
ν_t = total kinematic viscosity
ν_v = kinematic viscosity of vapor

ACKNOWLEDGEMENTS

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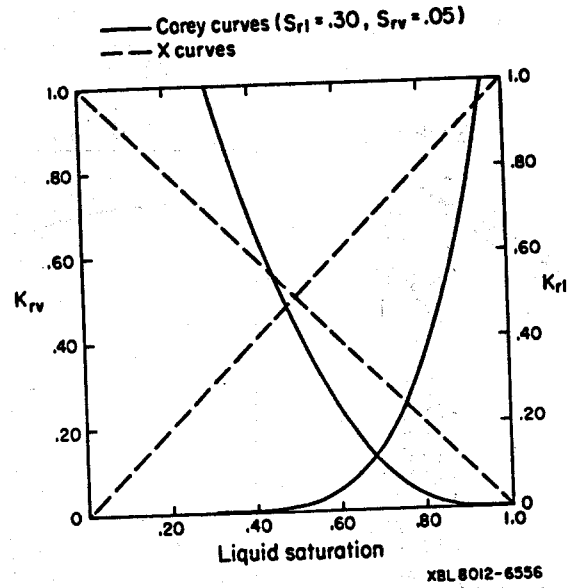

FIGURE 1. The Corey and the "X" relative permeability curves.

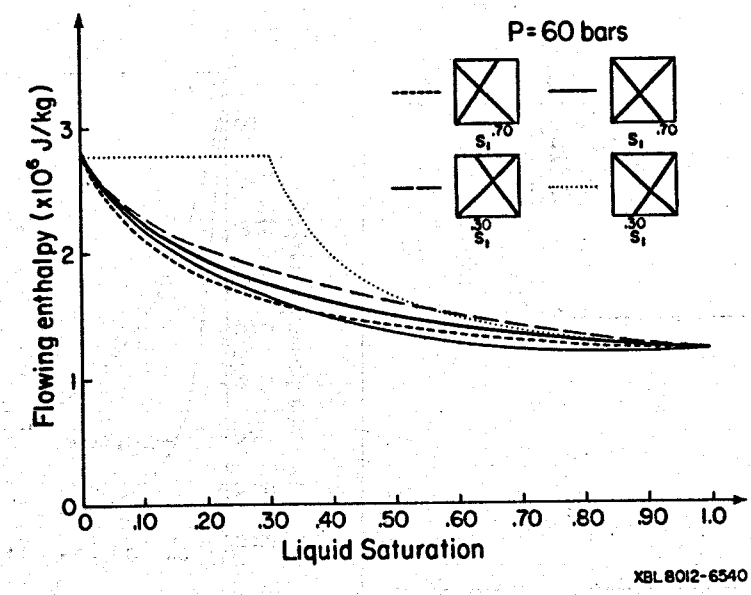

FIGURE 2. The relationship between flowing enthalpy and liquid saturation for linear relative permeability curves.

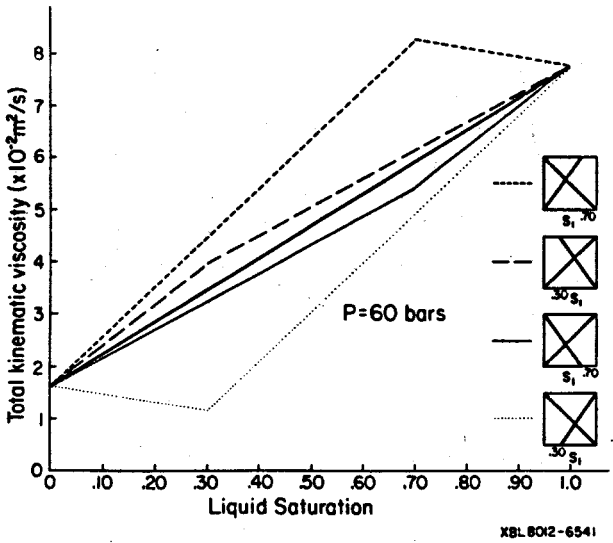

FIGURE 3. The relationship between kinematic viscosity and liquid saturation for linear relative permeability curves.

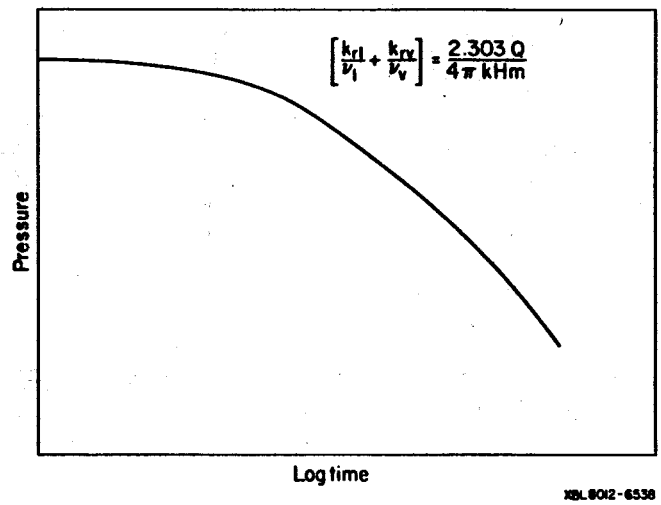

FIGURE 4. Pressure transient behavior during a well test in a two-phase reservoir.

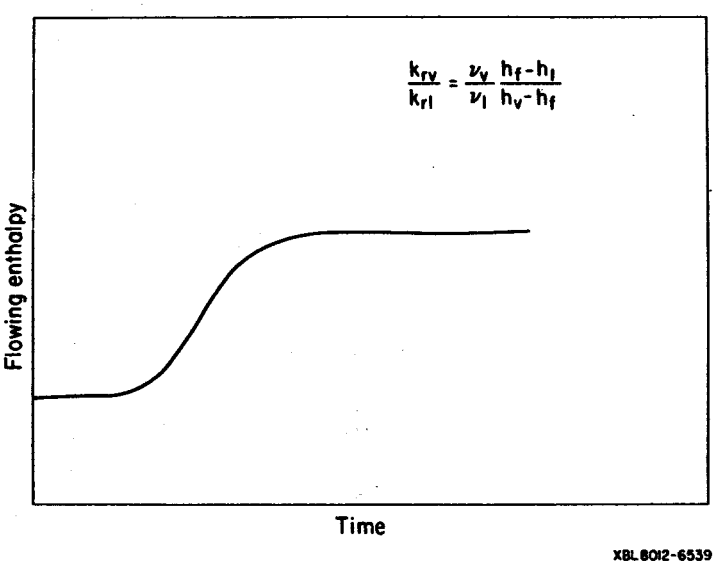

FIGURE 5. Flowing enthalpy during a well test in a two-phase reservoir.

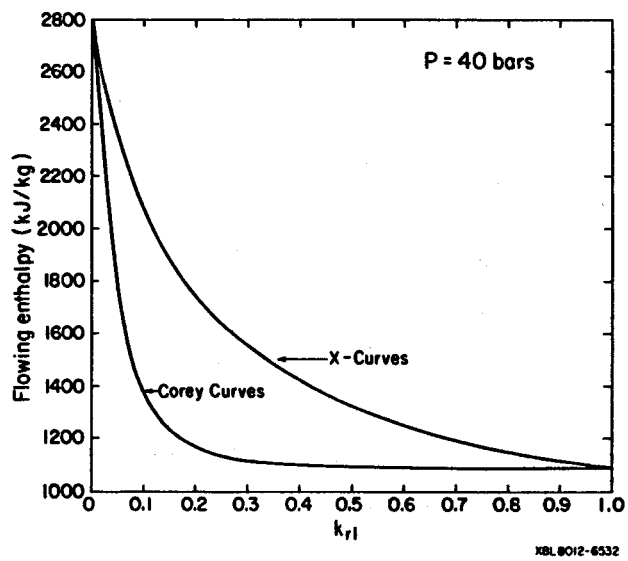

FIGURE 6. The relationship between flowing enthalpy and liquid relative permeability for Corey and "X" relative permeability curves.

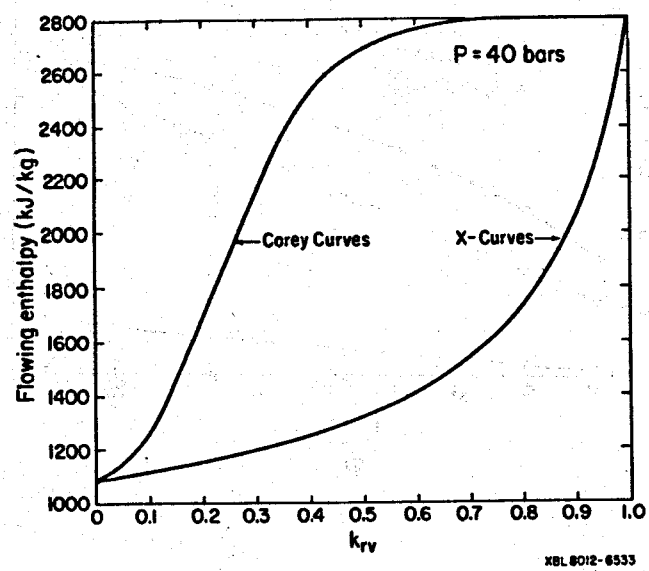

FIGURE 7. The relationship between flowing enthalpy and vapor relative permeability for Corey and "X" relative permeability curves.

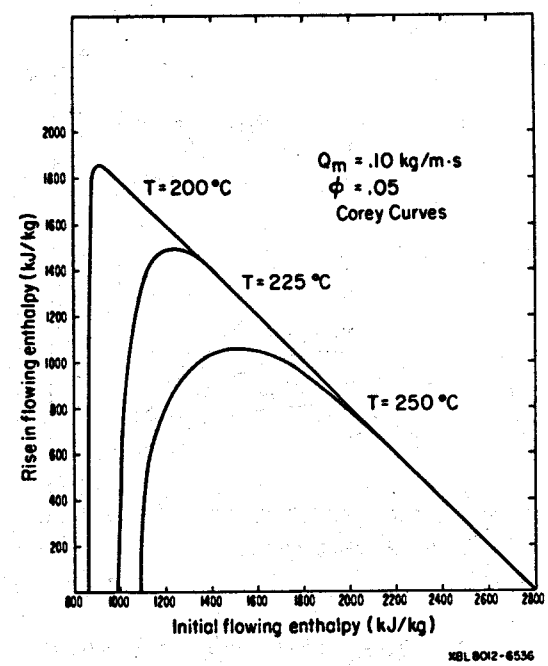

FIGURE 8. The relationship between the rise in flowing enthalpy and the initial flowing enthalpy for a porosity of ϕ = .05.

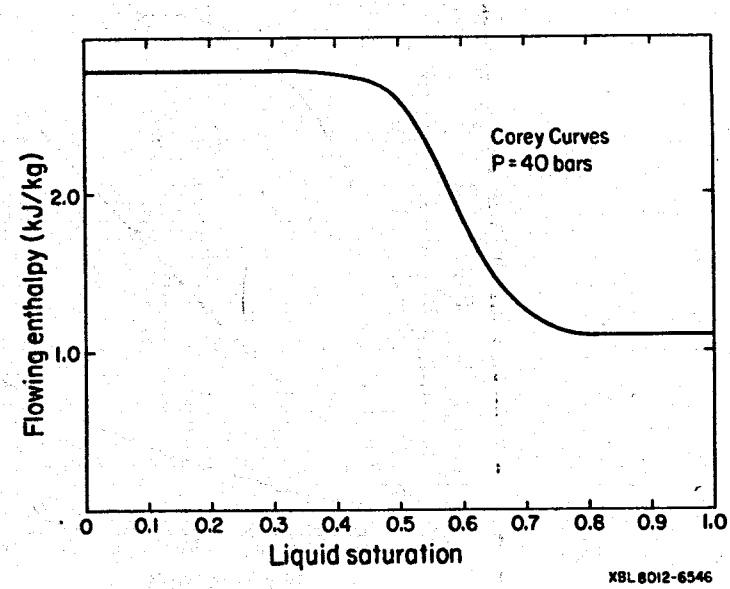

FIGURE 9. The relationship between flowing enthalpy and liquid saturation for the Corey relative permeability curves.

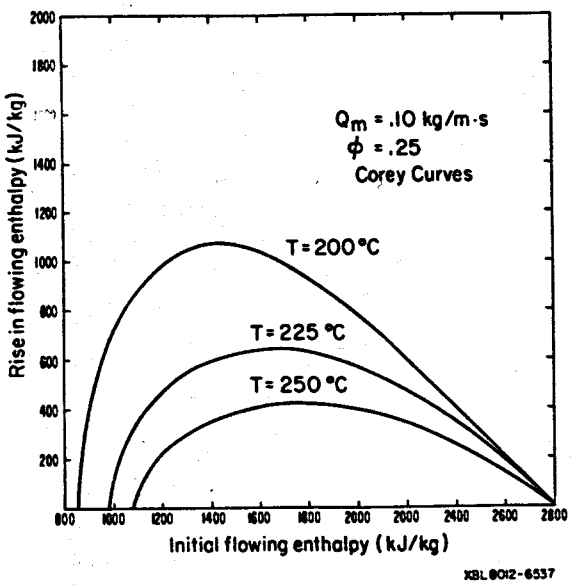

FIGURE 10. The relationship between the rise in flowing enthalpy and the initial flowing enthalpy for a porosity of ϕ = .25.

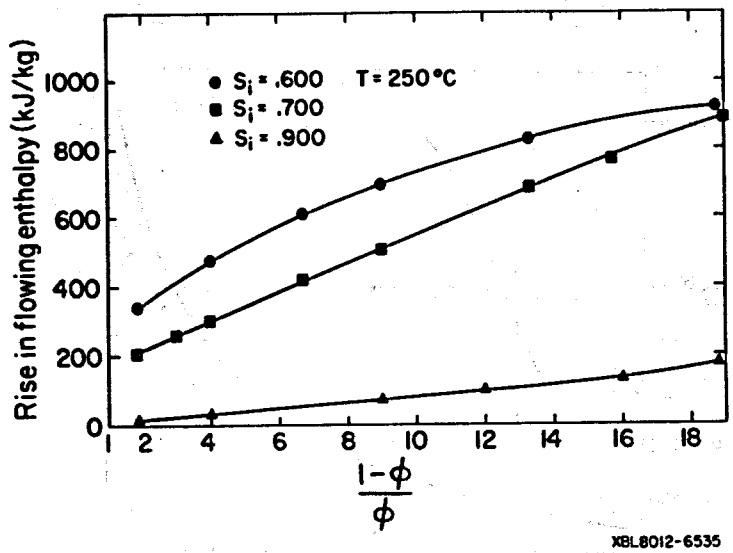

FIGURE 11. The relationship between porosity and the rise in flowing enthalpy.

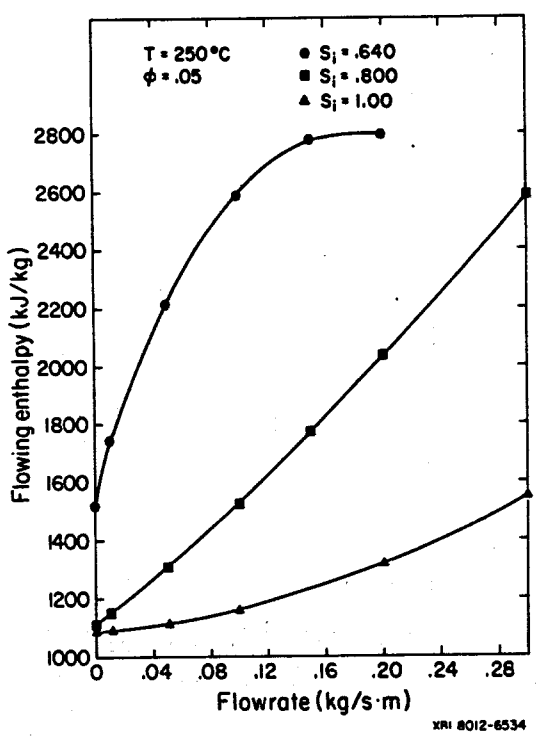

FIGURE 12. The relationship between flowrate and the rise in flowing enthalpy.