# INFLUENCE OF STEAM/WATER RELATIVE PERMEABILITY MODELS ON PREDICTED GEOTHERMAL RESERVOIR PERFORMANCE: A SENSITIVITY STUDY

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## INTRODUCTION/STATEMENT OF THE PROBLEM

The concept of relative permeabilities represents an attempt to extend Darcy's Law for single-phase flows through porous media to the two-phase flow regime.[1] In this regime, the flowrate of each phase is related to the macroscopic pressure gradient imposed on the flow through the relative permeability parameters $k_L$ (for the liquid phase) and $k_G$ (for the "gas" or vapor phase), expressed as fractions of the bulk permeability (k) of the medium to all-liquid flow. Accurate "models" for $k_L$ and $k_G$ as functions of some independent flow variable (historically liquid saturation) are required if one is to solve the complex two-phase flow problems associated with geothermal energy extraction, nuclear waste isolation, enhanced oil recovery and others.

Figure 1 shows a schematic of a generalized relative permeability model (RPM) which incorporates all of the features ("limits") potentially encountered for a two-phase, liquid/ vapor, flow through a porous medium. Here s is liquid saturation, defined as the fraction of the pore volume occupied by liquid; f, the dynamic quality of the flow, defined as the fraction of the total mass flowrate attributed to the vapor phase, $(W_G/W_L+W_G)$; k', the bulk permeability of the medium to all-vapor flow at a specified pressure (p). The four saturation limits of interest, and their corresponding flow regimes, are defined below:

A. $s(f\to0)$ is the saturation at which f goes to zero. Thus, for $s\geq s(f\to0)$, the vapor phase does not flow, i.e., it is "trapped" ($W_G=0$).
B. $s(k_L\to k)$ is the saturation at which $k_L$ goes to k. Thus, for $s\geq s(k_L\to k)$, the trapped vapor phase no longer influences the flow of the liquid phase.
C. $s(f\to1)$ is the saturation at which f goes to unity. Thus, for $s\leq s(f\to1)$, the liquid phase does not flow, i.e., it is "trapped" ($W_L=0$).
D. $s(k_G\to k')$ is the saturation at which $k_G$ goes to k'. Thus, for $s\leq s(k_G\to k')$, the trapped liquid phase no longer influences the flow of the vapor phase.

The occurrence of trapped phases is generally attributed to capillary effects.[1] For certain geologic materials, the saturation regime in which a trapped phase can exist may be quite extensive (e.g., Fig. 2-5 of Collins[2] presents data for sandstone cores indicating potential values for $s(f\to1)$ increasing from 0.2 to 0.7 as k decreases from $10^{-12}$ $m^2$ to $10^{-15}$ $m^2$). Should a trapped phase initially reside solely within the non-interconnected regions of the pore space, it would not be expected to influence the flow of the other phase. However, as the volume percent of a trapped phase increases, it may also begin to reside in portions of the interconnected flow channels within the porous medium. At this point, the trapped phase would begin to adversely affect the flow of the other phase. For these reasons, restrictions must be imposed on the above-noted limits:

$$s(k_G \rightarrow k') \leq s(f \rightarrow 1) \text{ and } s(k_L \rightarrow k) \geq s(f \rightarrow 0)$$

Further, since the vapor phase is a "gas," $k' > k$ due to molecular effects, with $k'$ approaching $k$ "from above" only as pressure becomes infinite. It can be seen, therefore, that the functions $k_L(s)$ and $k_G(s)$ depend on the "physical properties" of both the working fluid and the porous medium. Hence, no universal correlation for these functions can exist. Such models must be determined experimentally for each fluid/medium combination of interest.

A state-of-the-art computer code currently utilized to predict geothermal reservoir performance (SHAFT[3]) incorporates a RPM based on the oil/gas data analysis of Corey.[4] In its current form, this model allows trapped phases to exist, but does not allow for either trapped phase to influence the flow of the other phase. Two saturation values are input, $s(k_G \rightarrow k)$ and $s(k_L \rightarrow k)$. However, the equations used to describe $k_L(s)$ and $k_G(s)$ in this model possessasymptotic limits which require $s(f \rightarrow 1)$ to be identical to the input value for $s(k_G \rightarrow k)$ and $s(f \rightarrow 0)$ to be identical to the input value for $s(k_L \rightarrow k)$. No dependence of $k_G$ on $p$ is modelled.

The objective of the present effort was to conduct a sensitivity study, using the SHAFT code[3], to demonstrate the influence of various RPMs on predicted geothermal reservoir performance. A basic model devised to accomplish this goal was one which would allow each of the four noted saturation limits to be specified (input) independently; $k_L(s)$ and $k_G(s)$ were then modeled as having a linear dependence on s between these specified limits. As with the Corey model, $k'$ was set equal to $k$.

Since the primary objective was to investigate a broad spectrum of possible "saturation limit" combinations, thereby requiring a relatively large number of computer runs, a one-dimensional problem was chosen for study (Fig. 2). An infinite porous reservoir containing liquid water at $p_1 = 10.4$ bars and $T_1 = 180°C$ was connected to a permeable stratum initially at the same pressure and temperature. The stratum was assumed to be bounded above and below by layers of impermeable rock. Heat conduction from these layers to the stratum was neglected. At time (t) zero, a well-bore was "joined" to the stratum, i.e., a boundary condition of $p_2 = 1.06$ bars was specified at the stratum exit. The transient problem was then solved for $p(x,t)$, $T(x,t)$ and $s(x,t)$ until a steady-state solution was achieved. In all cases, a short region of liquid water flow, followed by an extended region of two-phase, steam/water, flow was predicted to occur. Reservoir "performance" or "output" was quantified by the product of the total, steady-state, mass flux (W) and the mixture enthalpy (H) at the stratum exit (i.e., into the well). All such steady-state convective energy fluxes (WH) were non-dimensionalized by the product ($WH_{REF}$) predicted to occur at the same location for a "reference case" RPM. The reference case utilized in the present study is one which possessed no trapped phases, while still maintaining the stated linear dependence of $k_L$ and $k_G$ on s.

## RESULTS

Consistent with the scope of the present investigation, it was first necessary to define an absolute permeability for the stratum which would meet the following two criterion: "low enough" to be representative of consolidated geologic materials, i.e., those capable of "trapping phases," and "high enough" to ensure that the problem remained convection dominated.

The reservoir problem was first solved with k as the primary independent variable ($10^{-12} \leq k \leq 10^{-16}$ $m^2$), incorporating several representative $k_L(s)$, $k_G(s)$ models utilized in the sensitivity study itself. Results showed non-dimensionalized reservoir output to be insensitive to k, and energy transfer along the stratum to remain convection dominated, for all $k \geq \approx 10^{-14}$ $m^2$. Factoring in the "trapping effectiveness" data reported by Collins,[2] and the tradeoff between permeability and computer run time, a final choice for k, of $10^{-12}$ $m^2$, was made.

Detailed scrutiny of these solutions led to the discovery of some features which, at first, were puzzling, but, in the final analysis, were shown to be entirely consistent with the physics included in the analysis and the boundary conditions imposed upon it. In summary, predicted steady-state saturation distributions, for convection-dominated flows, were found to contain "discontinuities," or "zones of exclusion," from unity to $s(f \to 0)$ and from $s(f \to 1)$ to zero. Predicted $p(x)$, $T(x)$ and $f(x)$ distributions were found, however, to be continuous and "smooth." What this says is that, in the steady-state limit, no physical regions within the stratum were predicted to contain a trapped phase. However, under transient conditions, and under conditions where conduction effects were non-negligible, physical regions containing trapped phases were predicted to exist. The mathematical explanation for these solutions is reviewed below.

In the steady-state limit, the continuity equation reduces to $W=W_L+W_G$ = constant. Similarly, the energy equation reduces to $W_LH_L+W_GH_G + Q$ = constant, where Q is the axial conductive heat flux at any station along the stratum. Darcy's Law (the momentum equation) for each phase requires that $W_L \propto k_L\ (dp/dx)$ and $W_G \propto k_G\ (dp/dx)$. Within a finite s regime ($s(f \to 0) \leq s < 1$) let $k_G$ be set equal to zero. The momentum equation then dictates that $W_G=0$, the continuity equation dictates that $W=W_L$ = constant $>0$, and the energy equation, for convection-dominated flows ($W_LH_L+W_GH_G \gg Q$), dictates that $W_LH_L$ = constant. A combination of these latter two results thus requires $H_L$ = constant. For a two-phase mixture of water and steam in equilibrium, if $H_L$ = constant, then p and T must also be constant, hence $(dp/dx)$ must be zero. A mathematical inconsistency then arises, since, for $(dp/dx) = 0$, $W_L$ must also be zero, contrary to the continuity requirement. Therefore, no computational solutions can exist in the "zones of exclusion."

Systematic variations of the four independent saturation limits defined above were equivalent, therefore, to systematic variations in the following quantities: (a) the extent of the saturation regime within which steady-state two-phase flow solutions could be achieved, (b) the maximum values of $k_L$ and $k_G$ at the boundaries of this saturation regime, and (c) the slopes of the $k_L(s)$ and $k_G(s)$ curves within this regime. As noted, even though no physical regions within the stratum were predicted to contain a trapped phase, "interactions" between "incipient trapped" and flowing phases could still be "simulated" through items (a) and (b) above. Simply put, when $k_G$ first exceeded zero, $k_L$ could be "specified" as being less than one; alternatively, when $k_L$ approached zero, $k_G$ could be "forced" to approach a value less than one.

In an attempt to present results of this sensitivity study in a concise manner, two distinct correlating parameters were introduced. The first of these was $\beta$, defined as the ratio of the absolute values of the slopes for the $k_L(s)$ and $k_G(s)$ curves:

$$\beta \equiv \frac{|\Delta k/\Delta s|_G}{|\Delta k/\Delta s|_L} = \left[\frac{s(k_L \to k) - s(f \to 1)}{s(f \to 0) - s(k_G \to k)}\right] \gtrless 1$$

This parameter is a measure of the incremental change in the mass flowrate ratio, $\Delta W_G/\Delta W_L$, for an incremental change in s. Results plotted as a function of $\beta$ are shown in Figure 3.

For those cases where only a single trapped phase regime was specified in the RPM, reservoir performance was seen to depend solely on $\beta$. At $\beta$=1, a limit common to both "branches" in this plot, reservoir output was seen to be identical to that predicted for the reference case model. It may be concluded, therefore, that specifying trapped-phase regimes without allowing for "interaction" between the trapped and flowing phases has no net influence on predicted reservoir performance. As $\beta$ approached both zero (trapped liquid for all s) and infinity (trapped vapor for all s), reservoir output monotonically approached zero, consistent with mathematical arguments already discussed. Concerning "sensitivity," for "single-trapped-phase" RPMs, a $\pm$50% change in $\beta$ about 1 resulted in $\approx$20 to 25% reductions in predicted reservoir output. This correlating approach proved unsatisfactory, however, since calculations using "two-trapped-phase" RPMs yielded results which fell everywhere below the two "envelope curves" just discussed.

A more successful correlation resulted with the introduction of $\Gamma$:

$$\Gamma \equiv \left[\frac{s(f \to 0) - s(f \to 1)}{s(k_L \to k) - s(k_G \to k)}\right] \leq 1$$

This parameter is a ratio of "saturation regimes": the numerator is the extent of the total saturation regime for which steady-state solutions can be obtained; the denominator is the maximum extent of the total saturation regime in which the two phases exhibit "interdependence." As such, this parameter is a "measure" of all three quantities in the basic RPM subject to systematic variations (recall previous discussions). Results plotted as a function of $\Gamma$ are shown in Fig. 4.

Once again, two discrete "envelope curves" were found to exist, one for each "single-trapped-phase" RPM. However, in these coordinates, the two curves were nearly identical, with all predictions for the more general "two-trapped-phase" RPMs falling between them. In the limit of $\Gamma$=1, trapped phases are included in the RPM, but each trapped phase is not allowed to influence the flow of the other phase. As noted earlier for such cases, reservoir output was found to be identical to that predicted for the reference case RPM. In the limit of $\Gamma \to 0$, no steady-state solutions are possible, hence output approaches zero. Concerning "sensitivity," a +50% increase in $\Gamma$ resulted in a $\approx$25 to 35% reduction in predicted reservoir performance.

In closing, it should be noted that Γ equals one for all variations of the modified-Corey RPM. Consequently, all predictions of reservoir performance made utilizing this RPM were found to be insensitive to variations in the two specified (input) saturation limits.

REFERENCES

1. Scheidegger, A.E., "The Physics of Flow Through Porous Media," University of Toronto Press, 3rd edition, Toronto, Canada, 1974.

2. Collins, R.E., "Flow of Fluids Through Porous Materials," The Petroleum Publishing Co., Tulsa, Oklahoma, 1976.

3. Pruess, K., Schroeder, R. C., Witherspoon, P. A.,, and Zerzan, J. M., "SHAFT 78, A Two-Phase Multidimensional Computer Program for Geothermal Reservoir Simulation," Lawrence Berkeley Laboratory Report LBL-8264, Nov. 1979.

4. Corey, A. T., "The Interrelation Between Gas and Oil Relative Permeabilities," Producers Monthly, Nov., 1954, pp. 38-41.

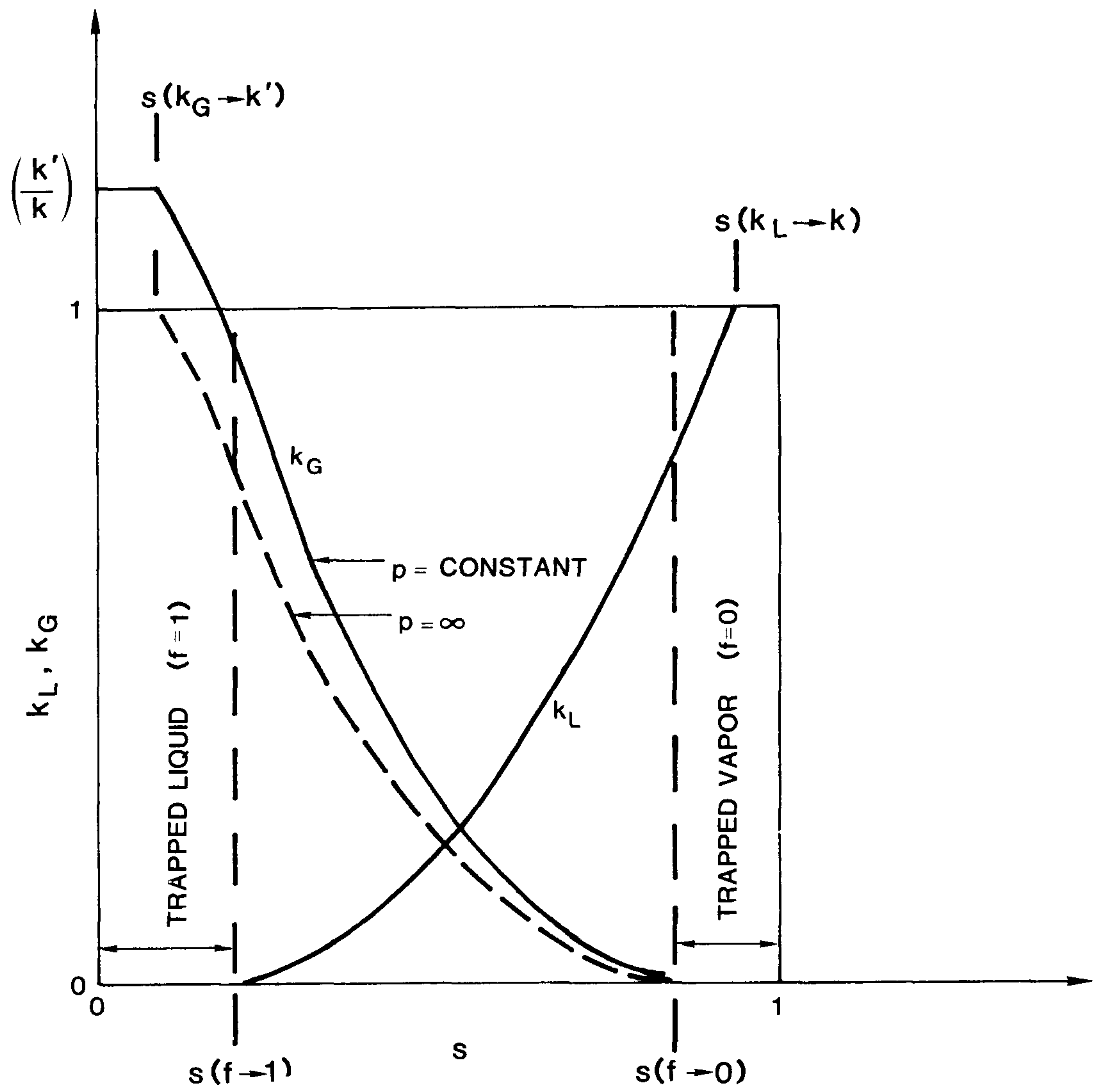


FIGURE 1

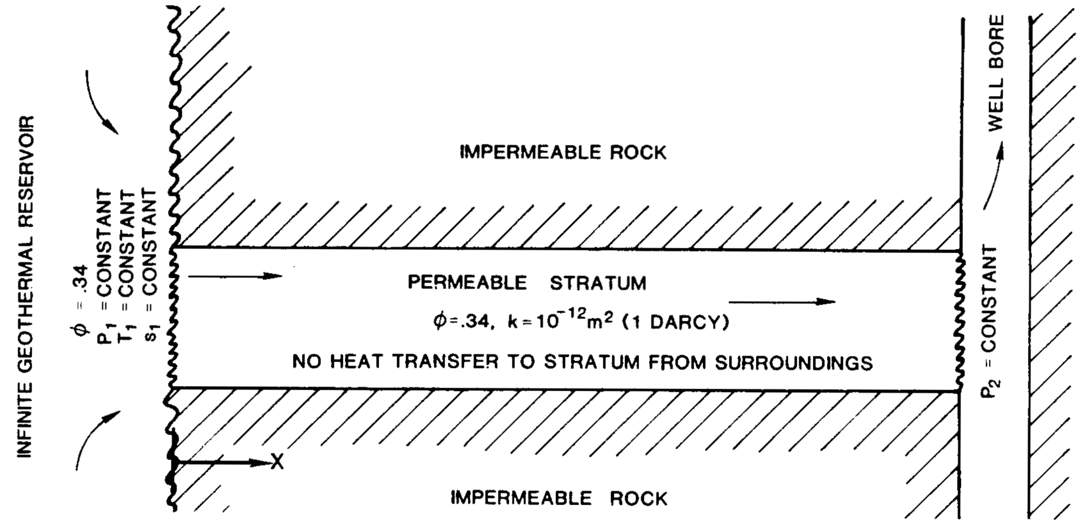


FIGURE 2

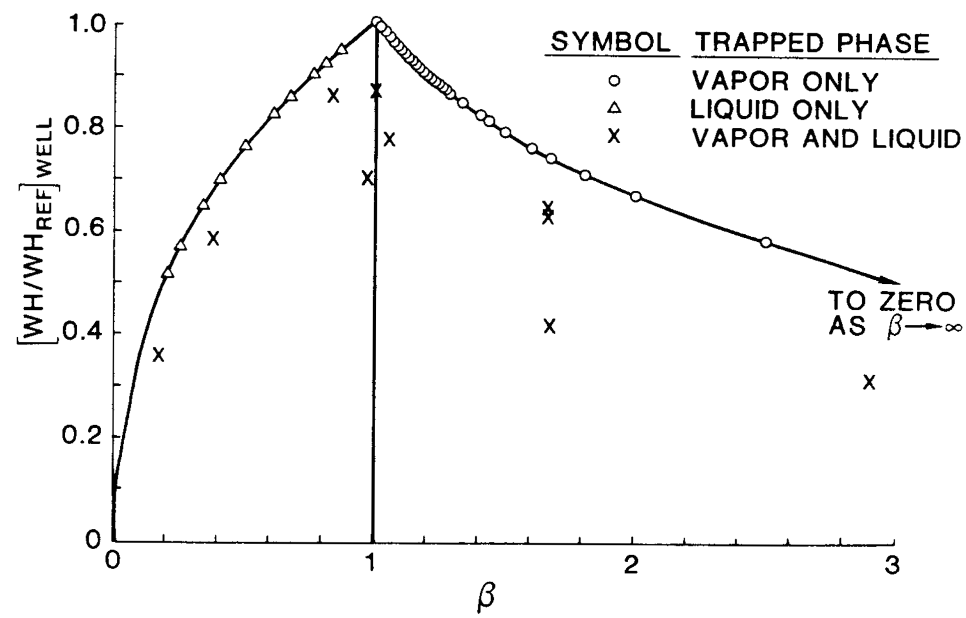


FIGURE 3

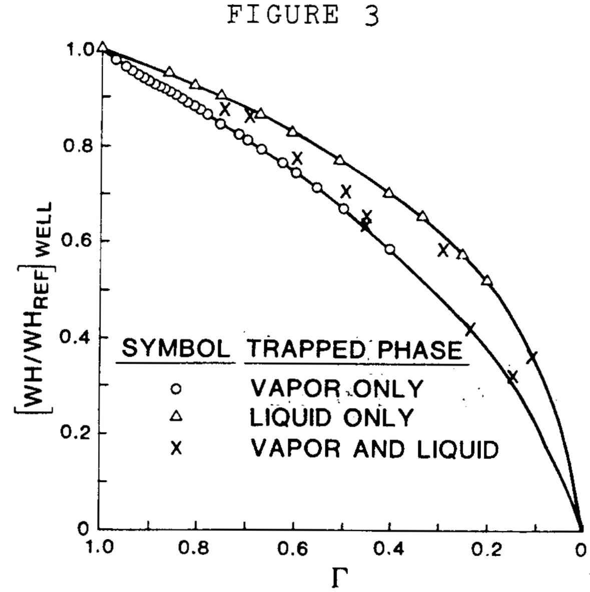


FIGURE 4