

Parametric Study of Reservoir Properties and Their Effect on Energy Recovery

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INTRODUCTION

Geothermal energy constitutes an important energy resource worldwide. Effective management of such a resource requires an understanding of a complex set of physical phenomena, including interphase mass transfer, convective transport of mass, and conduction and convection of energy. The coupled nature of these processes frequently requires that numerical simulation be used to investigate reservoir response to different management strategies.

The first stage of designing a simulation study of a particular reservoir involves defining the boundaries of the reservoir itself. We must determine the reservoir structure, the "edges" of the field, select the appropriate boundary conditions to be used, *ie*, whether pressure support from an adjacent aquifer is present, values of heat flux, etc. Having determined the three-dimensional extent and shape of the reservoir, we must identify the relevant fluid and petrophysical properties to be used in the simulation. In fractured geothermal systems, this data includes absolute and relative permeabilities for the fractures and rock matrix, fracture spacing and orientation, capillary pressure-saturation relationships, thermal conductivities, and others.

While it is fairly straightforward to identify the data required for accurate simulation of a geothermal reservoir, data acquisition is a different matter. Reservoir engineering is unique in the engineering disciplines in that much of the data is inferred by indirect means rather than being collected or measured. The data that can be measured (relative permeability, for example) can be of questionable reliability, in that the rock is removed from its native state, and conditions altered. Much of the data is also fit to empirical relationships; some is even estimated from these relationships. Due to the inherent uncertainties in this data, results of simulation studies using these data must be used with caution.

Of course, each of the variables noted above do not impact simulation results in the same way. In fact, errors in some of the data may exert little or no effect on our results. If that is the case, little effort need be expended by the geothermal operator to obtain this data. The problem is knowing which data exerts the most influence on simulation results, and therefore which should receive highest priority in acquisition efforts. The study presented in this paper seeks to answer this question by quantifying the effect changes in various parameters have on reservoir response to injection in a vapor-dominated reservoir. From a base case reservoir dataset we will examine differences in injectate recovery and steam energy produced as input data is varied. Parameters that are examined include relative permeability and capillary pressure relationships, fracture spacing, initial liquid saturations, and geologic structure.

DESCRIPTION OF THE BASE CASE

The base case selected for this study is an inverted 5-spot well pattern on 820 acre spacing. This well pattern exhibits symmetry in all four producers in homogeneous, isotropic media. Reservoir dimensions are 6000' x 6000' x 3600'. Structure has been neglected; the reservoir is a parallelepiped. Petrophysical properties, including permeabilities, porosities, and fracture spacing, are consistent with published Geysers data, and are summarized in Table 1. Relative permeability curves are also those typically encountered in Geysers simulations: Corey curves are used for matrix curves and straight line curves for the fractures. These are shown graphically in Figures 1-2. Capillary pressure has been neglected from the base case.

The mesh used in this simulation study is 11 x 11 areally, and 7 layers. Mesh refinement with depth is used, consistent with the findings of Lai and Bodvarsson (1991). The four producing wells are completed in the middle five layers, and injection occurs in the second layer (from the top).

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The simulator used in this study is TETRAD¹, a fully implicit, multi-phase, multi-component finite difference simulator. Details and validation of TETRAD are found elsewhere (Vinsome, 1991; Shook and Faulder, 1991).

The exploitation scenario for this study is as follows. Following a period of equilibration, the wells are produced on a surface flowing pressure constraint of 150 psia. At t=10 years injection begins, and 30% of the mass produced is reinjected. This is continued until t=30 years.

Selected results from this base case simulation are given in Figures 3-4. Figure 3 shows steam production history and steam quality for any one well (recall the symmetry). After an initially high rate, the wells decline harmonically at a rate of about 10%/yr. The steam is initially saturated, and a small amount of liquid is also produced. At t=10 years injection begins, and shortly thereafter the production history changes dramatically. The liquid production rate increases beginning 4 years after injection commences, and increases rapidly. Furthermore, from Figure 4 we see that most of the injectate is recovered as liquid; injection has quenched the reservoir bottom. In fact, at t=17.5 years the steam quality of produced fluids falls below 85%. This is the lower limit of allowable quality used in this study. For the purposes of this study, a well producing in excess of 15% liquid is assumed to be a "problem well", and any additional energy, mass, etc. from that well is excluded from further consideration.

An obvious comparison that can be made here concerns what impact injection had under these conditions. In order to make this comparison we have made another simulation of the base case model, but without any reinjection of the produced mass. Cumulative steam energy recovery histories for these two cases are given in Figure 5. As can be seen from this figure, injection in this particular case was not beneficial with respect to energy recovery. In fact, average pressures and temperatures are lower in the base case than in the no-injection case, due to the quenching of the bottom of the reservoir. Furthermore, since much of the injectate was recovered as liquid, there is not an appreciable difference in final mass in place between the two runs. Of course, different well completions could have offset the unfavorable breakthrough of liquid; however, such changes were not investigated. The point to note here is that injection does not necessarily improve reservoir behavior in vapor-dominated geothermal reservoirs.

A PARAMETRIC STUDY

The Effect of Reservoir Structure

The first reservoir parameter that was varied was the reservoir structure. Two perturbations were made to the base case reservoir shape. The first change was to incorporate actual geologic structure to our reservoir description; we next included an accurate description of the top of the reservoir but used a flat reservoir bottom. These two cases are shown in Figures 6-7.

The reservoir structure shown in Figure 6 is an actual portion of southeast Geysers, as mapped by a cooperative industry effort (Thompson and Gunderson, 1989; Thompson, 1989). This case uses top of steam as the reservoir top, and top of felsite as the bottom. While the felsite is not, in general, the reservoir bottom, it is believed to be a good approximation in this portion of the field. Figure 7 uses the same structure map at the top of the reservoir and a flat bottom. In both cases the average reservoir thicknesses are the same as in the base case.

When we include structure to the base case reservoir description, the reservoir response to injection changes significantly. In Figure 8 we show cumulative, field-wide steam energy recovery histories for the three cases. The solid line in this figure is the base case; recall that all producers watered out at t=17.5 years. As can be seen from this figure, failure to include correct reservoir structure can drastically alter predicted results. This is true not only of rate of energy recovery, but also ultimate energy recovery and liquid breakthrough in wells. Top of structure tends to alter ultimate energy recovery, but has much less effect on rate of energy recovery. Therefore, while top of reservoir is an important piece of information in a simulation study, the reservoir bottom is the single most important piece of structural information.

Relative Permeabilities and Residual Saturations

Relative permeability expresses the ability of a fluid to move as a function of that fluid's saturation. Typical relative permeability curves used in geothermal simulations are given in Figures 1-2. Corey relative permeability curves are often used for the matrix, while straight line relative permeabilities are assumed for the fractures. Two important differences exist between the curves shown in these figures. First, note that the use of Corey curves results in a large "total mobility hole" at intermediate liquid saturations. This means that, for a given pressure drop, both phases are less able to flow and therefore a lower total flow rate occurs. Second, note the differences in residual saturations between the two curves. It is frequently assumed that negligible phase trapping occurs in the fractures, whereas in the matrix fairly large residual saturations have been assumed. It should be noted that

direct measurements of relative permeabilities and residual saturations have not been made on Geysers rock.

Three sensitivity studies were made to the base case relative permeability curves. Two of the runs involved changes to the relative permeability curves in the fractures. The straight line curves were replaced by Corey curves, once using the same residual saturations as in the matrix, and the other using the Corey curves but no residuals in the fractures. A third run was made to look at variations in liquid mobility in the matrix. For this run, the liquid exponent in the matrix was changed to 2.5, approximately the largest liquid mobility in the matrix that would still flash to steam upon entering the fractures (Pruess and Narasimhan, 1982). Results from this study are given in Figure 9. As can be seen from this figure, steam energy recovery appears fairly sensitive to fracture relative permeability functions. Also, note that the use of Corey curves with and without residual saturations in the fractures resulted in virtually identical energy recovery histories. It follows, then, that reservoir response varied because of the shape of the relative permeability curves used. Thus, the "mobility hole" noted above accounted for the delay in liquid production, and the related increase in energy recovery.

Capillary Pressure and Initial Matrix Saturations

Two additional petrophysical properties and conditions that are difficult to measure are capillary pressures and initial matrix liquid saturations. Capillary pressures have historically been neglected in geothermal simulations, probably due to the lack of measurements. Values used for initial matrix saturations have varied from 50% to over 80%. Recent studies have suggested that a fairly large initial liquid saturation existed at The Geysers, based in part on Pruess' study of the evolution of a vapor-dominated reservoir from a liquid-dominated one (1985), and a field-wide history match study by Williamson (1990). Of course, there are now areas of The Geysers that are experiencing superheat conditions, so liquid saturations can vary from a large, virgin value to zero.

The capillary pressure curve used in this study is based on a fairly conservative scaling of Leverett J-function (Leverett, 1941), and is given in Figure 10. No attempt was made to account for possible hysteresis due to imbibition or drainage. Two different initial liquid saturations were also considered; the base case value of 0.8, and a second case of 0.4. Each of these cases was run with and without capillary pressure.

Intuitively, one would expect incorporation of capillary pressures at a large liquid saturation to have little effect. This is

borne out in this study, as shown in Figure 11. Given the relatively small capillary pressure at a liquid saturation of 0.8, the injectate imbibes only slightly. This results in a moderate (1.5 year) delay in liquid breakthrough, and a small increase in energy production.

Both a lower liquid saturation, and also capillary pressures at this lower saturation play a more important role in reservoir response. Figure 12 shows energy recovery histories for the base case, the base case with lower initial liquid, and the case of lower liquid saturation and capillary pressure. The case of lower liquid saturation results in less pressure support from the matrix, and therefore a reduction in both energy recovery rate and cumulative energy recovered. When capillary pressure is included in this run, however, response to injection changes appreciably. The injectate imbibes strongly into the matrix, resulting in a drastic (over 10 year) increase in liquid breakthrough time. This in turn results in nearly a 40% increase in energy recovery over the lower liquid saturation case. Thus, capillary pressures can have a dramatic effect on simulation results, but are much more important at low liquid saturations for the capillary pressure curves used here.

Fracture Spacing and Shape Factors

The final studies presented here concern dual porosity parameters. In simulating this fractured reservoir, we have used the Warren and Root dual porosity formulation (Warren and Root, 1963), with fracture spacing of 150' and the shape factor as defined by Gilman and Kazemi (1983). The shape factor for square matrix blocks is given as:

$$\sigma = 12/L^2$$

where L is the fracture spacing. Defining the correct shape factor has been an ongoing concern in the petroleum literature since the original Warren and Root work. Shape factors as large as $60/L^2$ have been used. Rossen and Shen (1989) point out that the shape factor depends on the process being modelled, and therefore one is unable to determine in advance what shape factor should be used.

In this study we have varied both fracture spacing and shape factors. Fracture spacing was varied from 150' to 300', with the attendant reduction in shape factor. The shape factor was then changed in another run from $12/300^2$ to $48/300^2$, which corresponds to the shape factor used in the base case run.

Results from this study are given in Figure 13. Clearly, both fracture spacing and shape factor both impact simulation results. Errors associated with either of these input parameters can drastically alter our predictive ability. There has been to date virtually no research on shape factors for

geothermal simulations; this study points out the need for such research to be done.

SUMMARY AND CONCLUSIONS

This paper has examined the influence of several reservoir parameters and conditions on steam energy recovery in the presence of injection. On the basis of this work, we draw the following conclusions:

Reservoir structure plays an extremely important role in correctly modelling injectate movement and energy recovery. Knowing the location and shape of the reservoir bottom is the single most important piece of structural information.

Fracture relative permeability curves affect reservoir response in injection, primarily because of the presence - or lack thereof - of a "mobility hole" seen in the Corey curves. Residual saturations in the fractures do not have much affect on reservoir behavior.

Capillary pressures can have an important affect on energy recovery, but primarily at low liquid saturations.

Parameters used in the dual-porosity approach of simulating fractured media are extremely important, and cause large variations in simulation results.

Much additional work is required to improve our simulation abilities. Research topics of interest include measurements of relative permeability and capillary pressure-saturation relationships, improved estimates of reservoir bottom, and the development of the correct shape factor for use in geothermal simulations.

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Table 1. Summary of Properties and Initial Conditions Used

Reservoir Properties and Initial Conditions	Matrix	Fractures
Porosity	0.045	0.02
Permeability (md)	0.01	10.
Relative Permeability:		
Liquid	$k_{rl} = S^4$	$k_{rl} = S_1$
Steam	$k_{rg} = (1-S)^{2.5}$	$k_{rg} = (1-S_1)$
	where $S = (S_1 - S_{1r}) / (1 - S_{1r} - S_{gr})$	
Residual Saturations:		
Liquid	0.3	0
Steam	0.05	0
Initial Saturations	$S_1 = 0.8$	$S_1 = 0.0008$
Initial Pressure = 500 psig @ Top of Reservoir (1000' SS)		
Initial Temperature = 470° F @ Top of Reservoir		
Rock Heat Capacity = 0.238 BTU/lb		
Rock Density = 165 lb/ft ³		
Rock Thermal Conductivity = 40 BTU/lb° F D		
Fracture Spacing = 150'		

Grid Data

NX = 11	NY = 11	NZ = 7
$\Delta x = 545.5'$	$\Delta y = 545.5'$	$1250' > \Delta z > 66'$

Figure 1. Corey Relative Permeability Curves

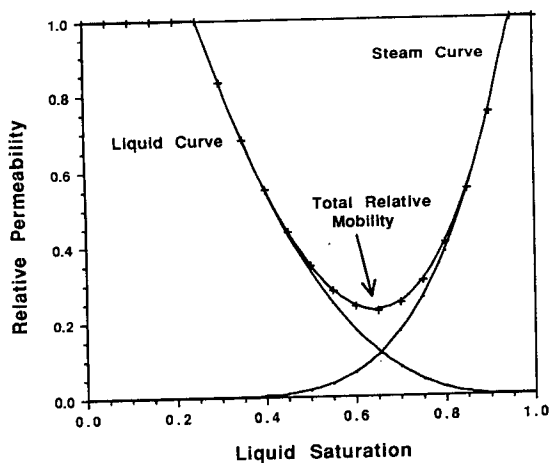


Figure 2. Straight Line Relative Permeabilities

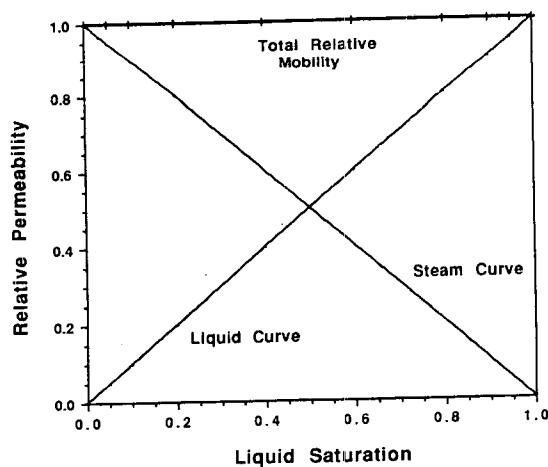


Figure 3. Steam Rate and Quality vs Time for Base Case.

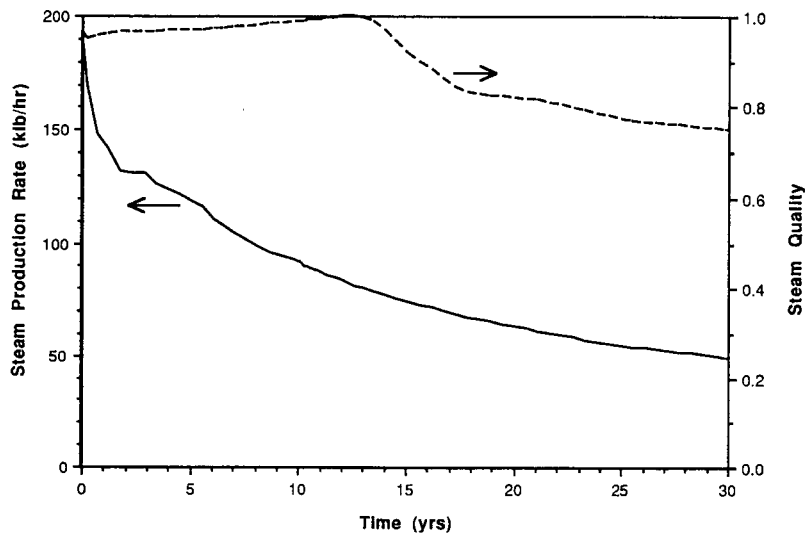


Figure 4. Tracer Recovery Histories for the Base Case.

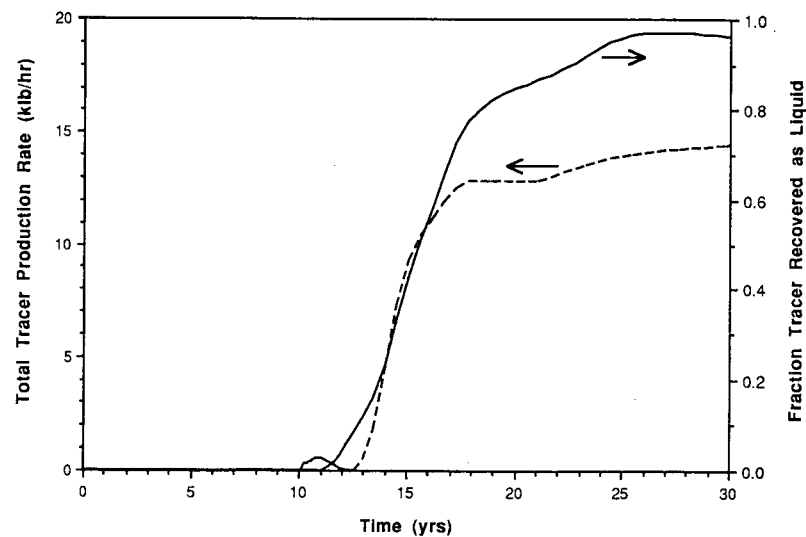


Figure 5. Comparison in Steam Energy Recovery for 30% Reinjection vs No Injection Case

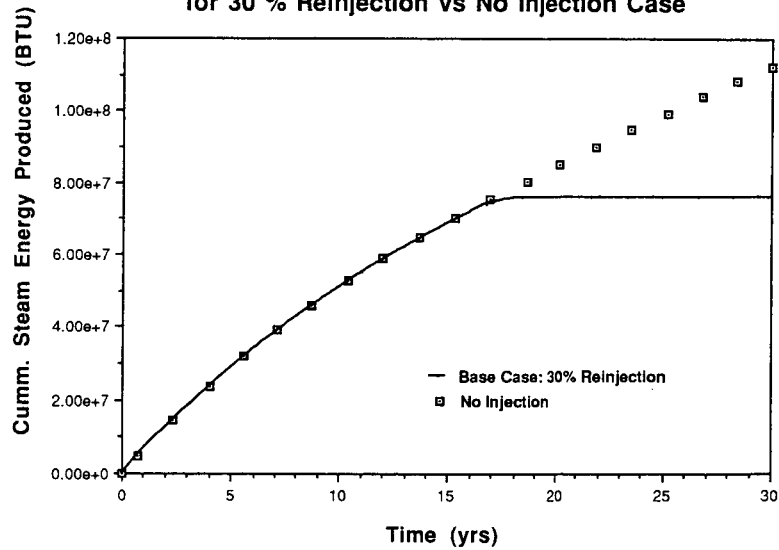


Figure 6. Reservoir Structure Case 1, Actual Portion of SE Geysers

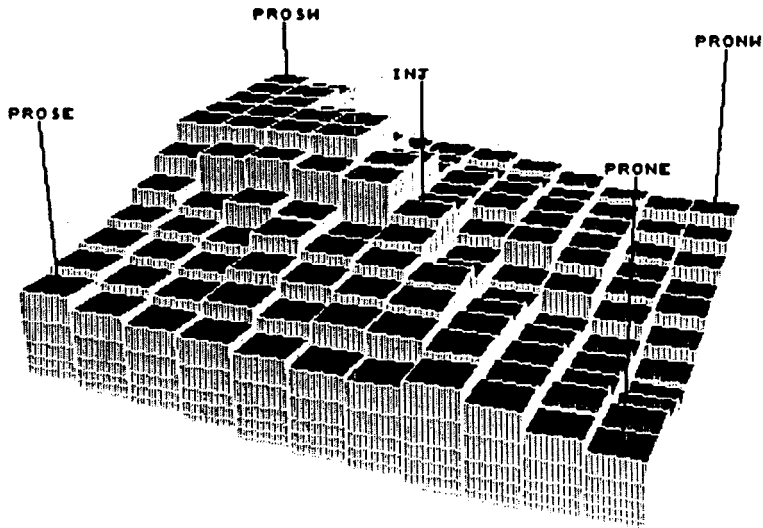


Figure 7. Reservoir Structure Case 2, Structure at Top, Flat Bottom

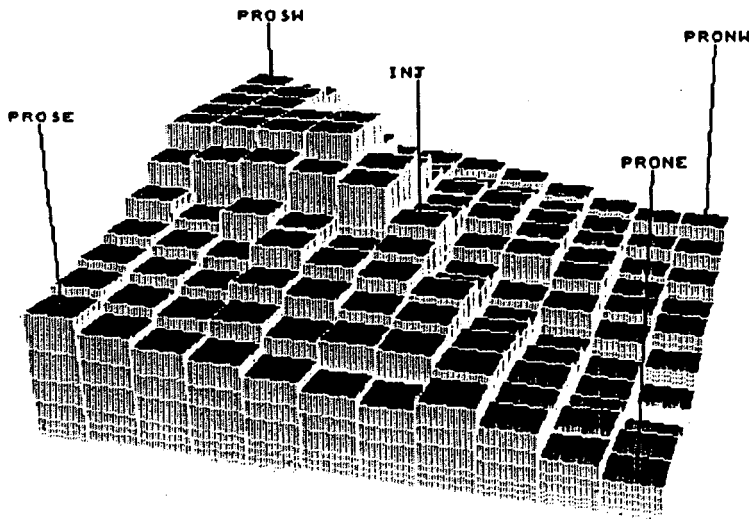


Figure 8. Energy Recovery as a Function of Reservoir Structure

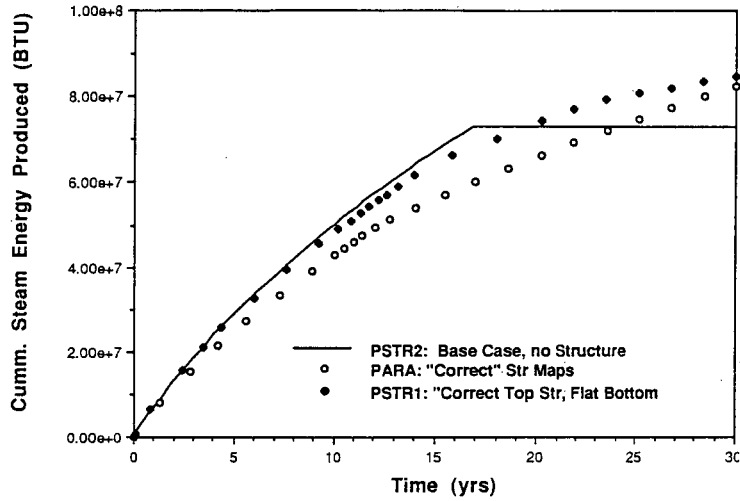


Figure 9. Energy Recovery as a Function of Relative Permeability Curves and Residual Saturations

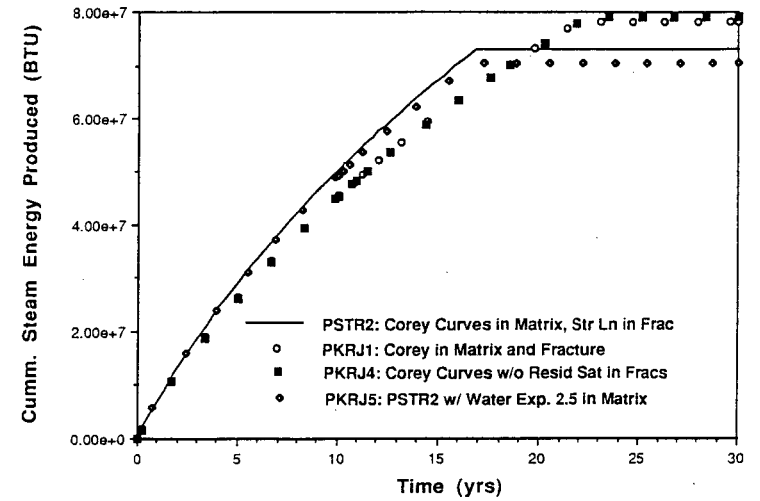


Figure 10. Capillary Pressure Curves Used.

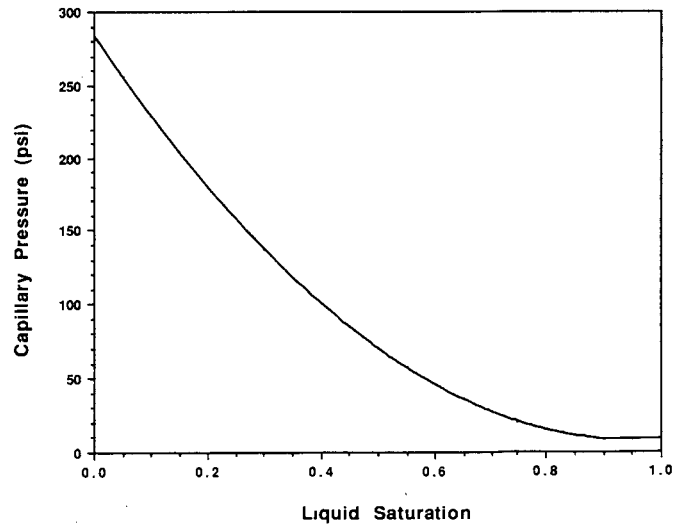


Figure 11. Energy Recovery as a Function of Capillary Pressure and Initial Saturations

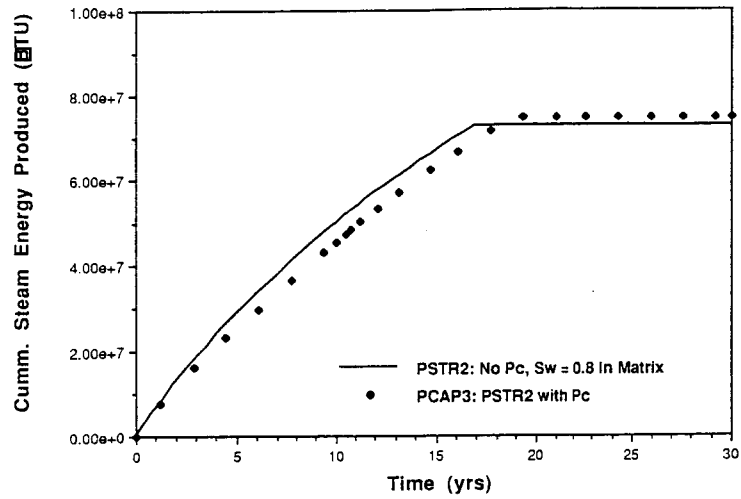


Figure 12. The Effect of Capillary Pressure on Energy Recovery at Lower Initial Water Saturation

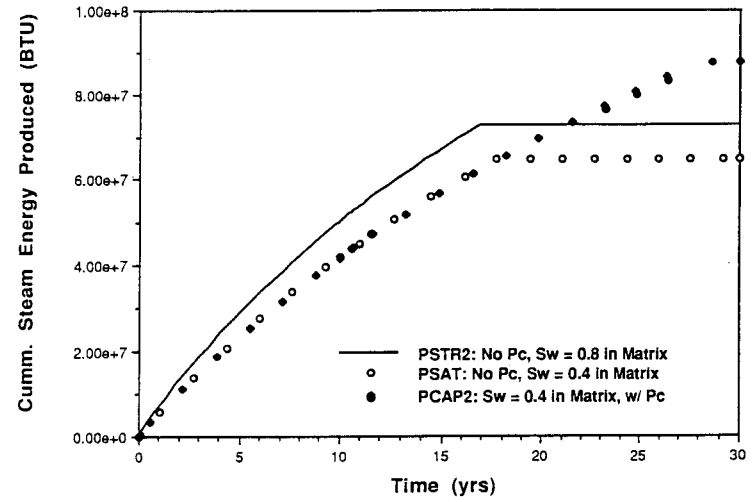


Figure 13. Energy Recovery as a Function of Fracture Spacing and Shape Factors Used

