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STEAM-WATER RELATIVE PERMEABILITIES FOR THE CERRO PRIETO GEOTHERMAL RESERVOIR

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ABSTRACT

We have refined a method used previously by several authors to estimate water-steam relative permeabilities. Our version provides also reasonable estimates of the corresponding saturations. It relies on production output data obtained by means of short tests. This constitutes a distinct advantage over the previous variants, which require long-term production data, because it allows early accurate assessments of reservoir reserves and producibility. Applying the refined version to data from 5 Cerro Prieto wells we obtained the corresponding relative permeabilities. These results indicate that the relative permeabilities are remarkably homogeneous over a wide area of the field, and over a considerable fraction of the reservoir thickness. They also provide independent evidence that fracture flow is important in Cerro Prieto. Finally, comparison of our results with those found for Wairakei shows that the relative permeabilities of geothermal reservoirs can be sensitively site-dependent.

INTRODUCTION

The shapes of the relative permeability curves exert an important influence on the mass and energy flows in geothermal reservoirs (e.g.Grant, 1977a, 1977b; Pritchett et al., 1980; Reda and Eaton, 1980;Bodvarsson et al., 1980; Grant et al., 1982). In particular, the choice of relative permeability curves significantly affects the interpretation of well tests in two-phase reservoirs, and numerical modeling of reservoir flows. In the past, it has been common practice to use Corey-type curves for such tasks, due mainly to the lack of reliable measurements of water-steam relative permeabilities. However, there is a growing body of evidence indicating that the relative permeabilities generally found in geothermal reservoirs significantly differ from the Corey curves (e.g. Grant et al., 1982; Pritchett et al., 1980; Menzies, 1982). Moreover, it is quite likely that relative permeabilities are site-specific. Thus, estimates of relative permeabilities for specific sites are highly desirable, both on theoretical and practical grounds.

Relative permeabilities are difficult to measure in the laboratory. Furthermore, laboratory determinations may be misleading, due to the usually fractured nature of geothermal reservoirs, which would require impossibly large rock samples in order to obtain results representative of the composite fracture-matrix medium. Therefore, field determinations of relative permeabilities are currently one of the most promising alternatives. A few attempts have been made in this respect (Grant, 1977a, 1977b; Horne and Ramey, 1978; Pruess and Bodvarsson, 1983). These authors have based their results on modified versions of an original idea by Grant (1977b). With the exception of Horne and Ramey's (1978), none of these variants provided a relationship between the inferred relative permeabilities and the corresponding saturations.

This paper presents a refined version of Grant's method that provides reasonable estimates of the relative permeabilities and of the corresponding saturations. Unlike the previous attempts, which used as input long-term production data, this variant relies on information provided by production output curves. Our approach is presented in the next section. Its successful application to Cerro Prieto data follows inmediatly. The last section of the paper summarizes our findings.

METHOD

Grant's method is based on the observed existance of a correlation between the mass flowrate and the flowing enthalpy. The basic equations (nomenclature at the end of the paper),

$$W = akA(\text{grad } p)\ \{(k_{rw}/\nu_w) + (k_{rs}/\nu_s)\} \quad (1)$$

$$h = \frac{h_w(k_{rw}/\nu_w) + h_s(k_{rs}/\nu_s)}{(k_{rw}/\nu_w) + ((k_{rs}/\nu_s)} \quad (2)$$

relate the sought-after relative permeabilities with some measurable quantities (W, h), and with, in principle, unknown quantities such as k, A. grad p, ν_w, ν_s. To infer the relative permeabilities it is necessary to somehow estimate the unknown variables. The previous work has relied on different estimates of the unknown variables, all of them based on long-term production data. Our approach is based on information contained in production output curves.

In a previous paper (Iglesias et al., 1984) we have shown that the reservoir, pressure p_e and the productivity index J of water-fed wells can be obtained from production output curves. The process involves computation of bottomhole flowing pressures from wellhead mass flowrates and enthalpies. In this paper we take advantage of the accesibility of J and p_e to estimate the parameter group [a k A (grad p)]. When production tested, most Cerro Prieto wells behave as represented in Fig.1 (the arrows indicate the sense of increasing mass flowrate). The point (h_e, p_e) represents the unperturbed thermodynamic state of the reservoir fluid (liquid). As the flowrate increases, the bottomhhole flowing pressure drops isoenthalpycally, until the corresponding saturation pressure is intercepted. From then on, two-phase flow is established in the reservoir around the well. We use the portion of the production test data lieing on the isoenthalpic segment to infer J and p_e; the remaining data are used to estimate the relative permeabilities.

Assume that k, k_{rw}, and k_{rs} are homogeneous in the reservoir. Recall that

$$W^* = akA\ \text{grad } p)/\nu_w{}^* = J\{p_e - (p_{wf})^*\} \quad (3)$$

where W+, ν_w*, J, and (p_{wf})* refer to quantities on the isoenthalpic segment of Fig. 1. Then, solving (1) and (2) for k_{rs}, ,k and using (3), we get

$$k_{rs} = \frac{W}{J(p_e - p_{wf})}\ \frac{\nu_s}{\nu_w^*}\ \frac{h-h_w}{h_s-h_w} \quad (4)$$

$$k_{r\nu} = \frac{W}{J(p_e - p_{wf})}\ \frac{\nu_w}{\nu_w^*}\ \frac{h_s-h}{h_s-h_w} \quad (5)$$

where we have replaced $(p_{wf})^*$ by p_{wf}.

Equations (4) and (5) refer to a particular point in the reservoir: the sandface. At that particular point, and for given values of W and h, there is a corresponding value of the (steam) saturation S, calculable from h and p_{wf}. Therefore, different pairs (W,h), corresponding to different points on the two-phase portion of the curve shown in Fig. 1, allow computation of the relative permeabilities as functions of S from (4) and (5).

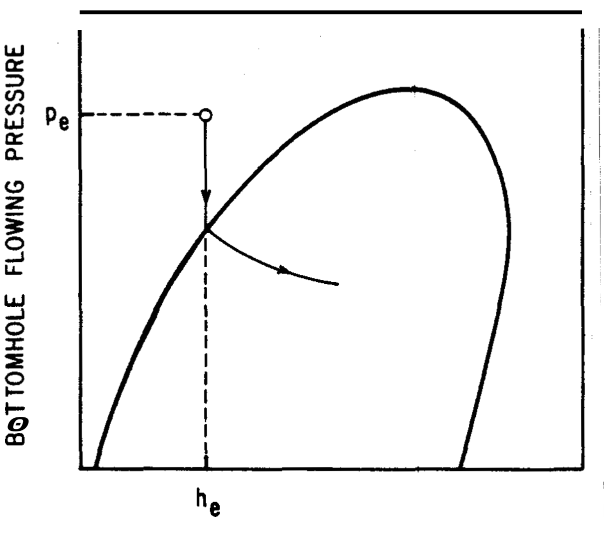

Fig. 1. Schematic of the thermodynamic evolution of the fluids at the sandface of Cerro Prieto wells during production tests. The arrows indicate the sense of increasing mass flowrate.

CERRO PRIETO RELATIVE PERMEABILITIES

We have applied the method just described to production output data from Cerro Prieto wells E-2, E-5, M-102, H-110, and M-125. Figure 2 shows the locations of these wells. Table 1 succintly describes the corresponding completions.

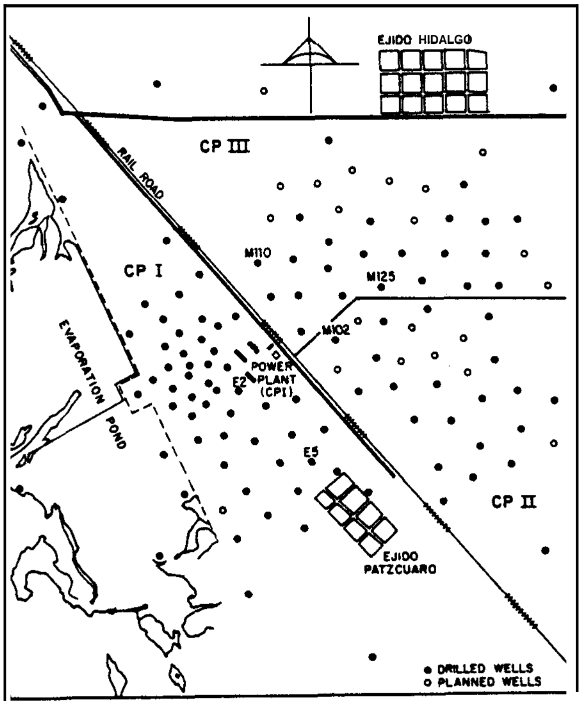

Fig. 2. Location of the wells involved in this work.

Table 1. Summary of well completions

Well	Depth (m)	Slotted Intervals (m)
E-2	1946	1702-1940
E-5	1965	1809-1963
M-102	1996	1793-1990
M-110	1856	1753-1853
M-125	2315	2028-2314

Our main results are summarized in Fig.3, which presents the computed relative permeabilities as functions of the corresponding steam saturations. The data used for this work were such that. steam saturations as high as 0.75 were inferred. Reliable extrapolation to higher steam saturations is thus facilitated.

The steam relative permeability points lie on a remarkably well aligned curve, despite the seemingly heterogeneous

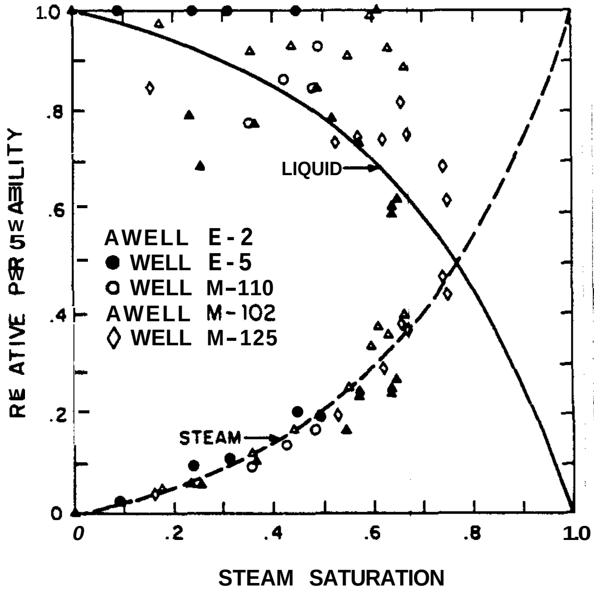

Fig. 3. Water-stem relative permeability functions from Cerro Prieto well data.

origin of the data (five different wells involved, each with its own local characteristics). The water relative permeability points display a considerable scatter, which is comparable to that foud in previous work (e.g. Grant, 1977b; Horde and Ramey, 1978; Pruess and Bodvarsson, 1983). This scatter propagates from the original raw data. The errors are estimated below.

Taking advantage of its smaller dispersion, we fitted the inferred steas permeability data with a curve of the form

$$\ln k_{rs} = B + C \ln S + D S \qquad (6)$$

Using a least squares technique we found

B = -1.85344,

C = 0.910184,

D = 1.82217.

Then, we noted that the sum of the water and steam relative permeabilities is, like for other geothermal reservoirs, close to unity (see Fig. 4). This characteristic has been atributed (e.g. Grant 1982) to the widespread existence

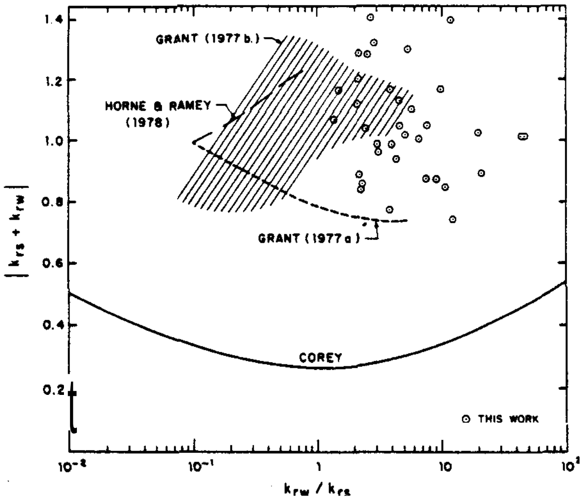

Fig. 4. The **sum** of the water and steam relative permeabilities for Wairakei and for Cerro Prieto (adapted from Grant et al., 1982).

of fractures in geothermal reservoirs: in fracture flow there should be no interference between both phases. Assuming the validity of the "fracture relative permeabilities" $k_{rw} + k_{rs} = 1$ (e.g. Grant 1982) we computed the water relative permeability curve shown in Fig. 3.

The average relative errors with respect to the curves in Fig. 3 are about 15% in both cases.

As shown in Fig. 4, $k_{rw} + k_{rs}$ is far closer to unity than predicted from Corey-type curves. This indicates that fracture flow is important in Cerro Prieto. This indication has been independently confirmed by standard well testing.

The wells involved in this work are disseminated throughout the field as shown in Fig.2. They also cover a relatively wide range of depths, as attested by the widths of the slotted intervals in Table 1. Therefore we conclude, on the basis of the discussions of the preceding paragraphs, that the homogeneity displayed by the relative permeability curves of the individual wells reflects a reservoir-wide property characteristic of the producing geological formations. This conclusion will have to be checked with data from more wells, since it was inferred from a relatively small sample of wells, however well chosen. Nonetheless, for the reasons discussed, the homogeneity of the steam/water relative permeabilities for, at least, the depth interval sampled, seems to be firmly based.

Comparison of the results of Fig. 3 with those found by Horne and Ramey (1978) for the Wairakei geothermal reservoir is interesting (Fig. 5). It clearly shows that relative permeabilities can be sensitively site-dependent. At this point we can only speculate that the existing differences between the Ceruo Prieto and the Wairakei relative permeabilities arise from the disparate chdracteristics of the sandstones of the former and of the ignimbrites and andesites of the later.

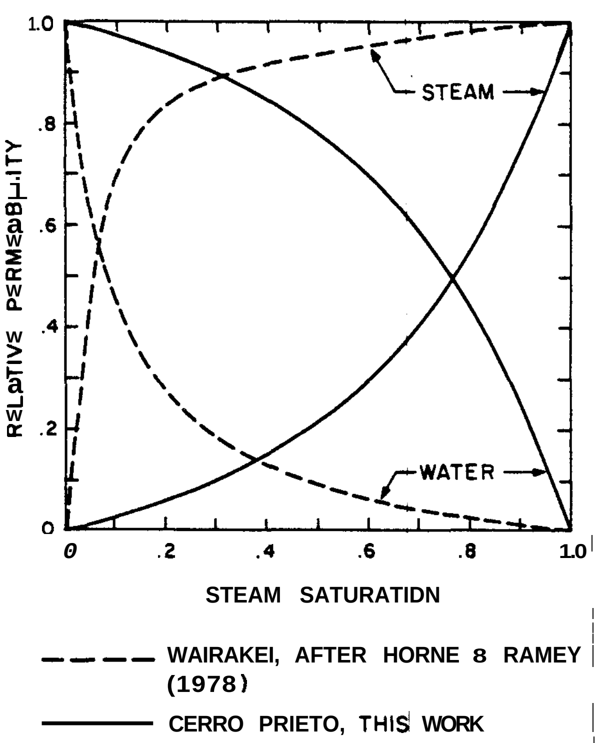

Fig. 5. Comparison of Cerro Prieto (this work) and Wairakei (Horne and Ramey, 1978) relative permeability functions.

SUMMARY AND CONCLUSIONS

We have refined a method, first proposed by Grant (1977b), and then adopted with variations by several authors, to estimate water-steam relative permeabilities. Unlike the previous versions, which used as input long-term production data, our variant relies on information provided by production output curves. This approach has the advantage of allowing relative permeability estimates early in the development of the field. The availability of these estimates permits early accurate assessment of reserves and producibility of the reservoir (recall that the relative permeability functions significantly affect the interpretation of well tests in two-phase reservoirs, and modeling of reservoir flows).

We have applied our method to data from 5 Cerro Prieto wells. The following conclusions can be drawn from our results.

The water-steam relative permeabilities for Cerro Prieto can be expressed by $\ln k_{rs}=-1.85344+0.910184 \ln S+1.82217S$, $k_{rw}=1-k_{rs}$. The scatter about these values is tipically 15%.

The inferred relative permeabilities are highly homogeneous over a wide area, and over a substantial depth interval of the reservoir.

As is the case for other geothermal reservoirs, the sum of the Cerro Prieto water-steam relative permeabilities is much closer to unity than to what would be expected for Corey-type curves. This is independent evidence indicating that fracture flow plays an important role in Cerro Prieto.

Finally, comparison of our results with those found for Wairakei by Horne and Ramey (1978) shows that the relative permeabilities of geothermal reservoirs can be sensitively site-dependent.

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NOMENCLATURE

a : a constant to acomodate different systems of units.

A : area normal to the fluid flow in Darcy's expression.

B : coefficient of least squares fit of k_{rs}

C : coefficient of least squares fit of k_{rs}.

D : coefficient of least squares fit of k_{rs}.

h : flowing specific enthalpy at the sandface.

h_e : reservoir specific enthalpy.

h_s : saturation steam specific enthalpy at sandface flowing pressure.

h_w : saturation water specific enthalpy at sandface flowing pressure.

J : productivity index.

k : absolute permeability.

k_{rs} : steam relative permeability.

k_{rw} : water relative permeability.*

p : pressure.

p_e : reservoir pressure.

p_{wf} : flowing pressure at the sandface.

S : steam saturation.

W : mass flowrate (total discharge).

ν_s : steam kinematic viscosity.

ν_w : water kinematic viscosity.

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