SGP-TR-20-4

PROCEEDINGS
SECOND WORKSHOP
GEOTHERMAL RESERVOIR ENGINEERING
December 1-3, 1976

Paul Kruger and Henry J. Ramey, Jr., Editors
Stanford Geothermal Program
Workshop Report SGP-TR-20*

*Conducted under Grant No. NSF-AER-72-03490 supported by the RANN program of the National Science Foundation and Contract No. E043-326-PA-50 from the Geothermal Energy Division, Energy Research and Development Administration.

DISCLAIMER

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

STEAM ZONE TEMPERATURE GRADIENTS AT THE GEYSERS

J. R. Hite and E. L. Fehlberg
Shell Oil Co.
P. O. Box 831
Houston, Texas 77001

Temperature logs, which have been run routinely in The Geysers geothermal wells, have been used to indicate the depth corresponding to the top of the steam zone (1). This steam chest is marked by temperatures which exceed 400°F and by a sharp change in temperature gradient. Above the steam chest heat transfer is largely by conduction, so that the gradient depends on heat flux and thermal conductivity. Within the steam chest, which is highly fractured, heat is transferred via the vertical fractures by convective reflux as well. This being a much more effective mechanism, the temperatures are more nearly isothermal (2). The existence of this abrupt gradient change has been confirmed directly in U.S. Geothermal C-4 and C-5, where the temperature was logged from the surface into the upper unproductive portion of the steam chest.

This report describes a model of the heat transfer within the steam chest. By comparing the model with temperature gradient data from a well, one can estimate the average vertical permeability within the reflux system.

Vertical Heat Transfer Mechanisms

The model is based principally on the description of the reservoir by Truesdell and White (2). They argue that the steam chest is a highly fractured rock system. Flow conductivity is due largely (or solely) to the fractures. The effective vertical permeability of the matrix rock is unknown as yet, but is probably quite small. Fluid storage is known to be relatively large, although its distribution with depth remains a matter of some controversy. It could be either in rock matrix porosity or in a bottom water zone at some unknown depth (15,000 ft?) or both. To yield the anticipated reserves at The Geysers, the fluid storage must be equivalent to a porosity of 6% over a depth of 5000 ft. on 40-acre spacing. The top of the steam chest is presumed to be an unfractured rock seal. (The seal is probably at least partially broken in the Old Geysers Area.)

To model the temperature gradient within the steam chest the equations of continuity were solved for a combination of steam reflux within the fractures and thermal conduction through the rock matrix. Steady state conditions were assumed and horizontal gradients were neglected. Rock and fracture properties were constant with depth. Flow in the fractures (vapor phase up, liquid phase down) was modeled using Darcy's Law, assuming straight line relative permeabilities for each phase ($k_{rp} = S_p$). This would be correct for laminar flow in fracture geometries equivalent to narrow slits. At the top of the steam chest it was assumed that the net mass flux was zero and that the heat flux was equal to $-k^T \left.\frac{dT}{dz}\right|_o$ where k^T is the thermal conductivity and $\left.\frac{dT}{dz}\right|_o$ is the temperature gradient just above the steam chest. The resulting equations the predict temperature and pressure versus depth as a function of 1) steam properties, 2) the assumed pressure at the top of the steam chest, P_o, 3) the ratio of thermal conductivity k^T, to the average vertical permeability in the reflux system, k_v, and 4) the product of this ratio and the gradient $\left.\frac{dT}{dz}\right|_o$.

U.S. Geothermal C-4 and C-5 Temperature Gradients

The temperature vs. depth curves shown in Fig. 1 were derived from Horner-type buildup analyses as suggested by Dowdle and Cobb [(3)]. Two separate log runs were made in each well, one at the 13-3/8" casing point and one at the 9-5/8" casing point. Each run consisted of several traverses over depth and a build-up at TD. The surveys did not include the productive part of the steam zone.

The data show a sharp gradient change approximately corresponding to the top of the steam reflux zone. Below that depth the gradient is greatly reduced, although still significantly greater than that which would result from a static steam phase.

Results

The calculated temperature gradients are compared to the well data in Fig. 2 for several assumed values of k_v. The assumed values for the other parameters are:

C-4	C-5
$\left.\frac{dT}{dz}\right\|_o$ = 12.2° F/100 ft (222°C/km)	$\left.\frac{dT}{dz}\right\|_o$ = 11.3°F/100 ft (206°C/km)
k^T = 29.0 Btu/day-ft-°F (.005 cal/sec-cm-°C)	k^T = Same as C-4
P_o = 425 psia (29.32 bars)	P_o = 316 psia (21.77 bars)
T_o = 450.6°F (232.6°C)	T_o = 422.0°F (216.7°C)

The pressure, P_o, is the saturation pressure corresponding to the measured temperature, T_o, at the top of the steam chest. The best match of computed and actual gradients corresponds to k_v = 0.5 md for C-4 and k_v = 0.2 md for C-5. The accuracy of this result is affected by the accuracy of the temperature measurements as well as by the many assumptions in the model. A study of the sensitivity of k_v to the other parameters shows that it is roughly proportional to the assumed values of k^T and $\left.\frac{dT}{dz}\right|_o$.

These results were obtained using data from the unproductive part of the steam chest. As a result the calculated permeability values are much less than would be expected from a productive interval.

The model can also be used to extrapolate pressure and temperature to greater depths whenever the temperature gradient at those depths can be reliably predicted.

Conclusions

The model suggests that the average vertical permeability at The Geysers is less than 1 md in the upper unproductive portion of the steam chest.

Temperature data taken from this portion of the steam chest indicate that the reservoir is considerably less isothermal than previously assumed. The dynamic effects of the reflux system should be included in any study of transient well behavior or in any estimate of deliverable reserves.

References

(1). Fehlberg, E. L. (1975), "Shell's activity in The Geysers Area," presented at the Stanford Geothermal Workshop, Stanford University, December 15-17.

(2). Truesdell, A. M., and White, D. E. (1973), "Production of superheated steam from vapor-dominated geothermal reservoirs," Geothermics, Vol. 2, p. 154.

(3). Dowdle, W. L., and Cobb, W. M. (1974), "Estimation of static formation temperature from well logs," SPE Preprint SPE 5036.

FIGURE 1
ESTIMATED STATIC TEMPERATURE GRADIENTS

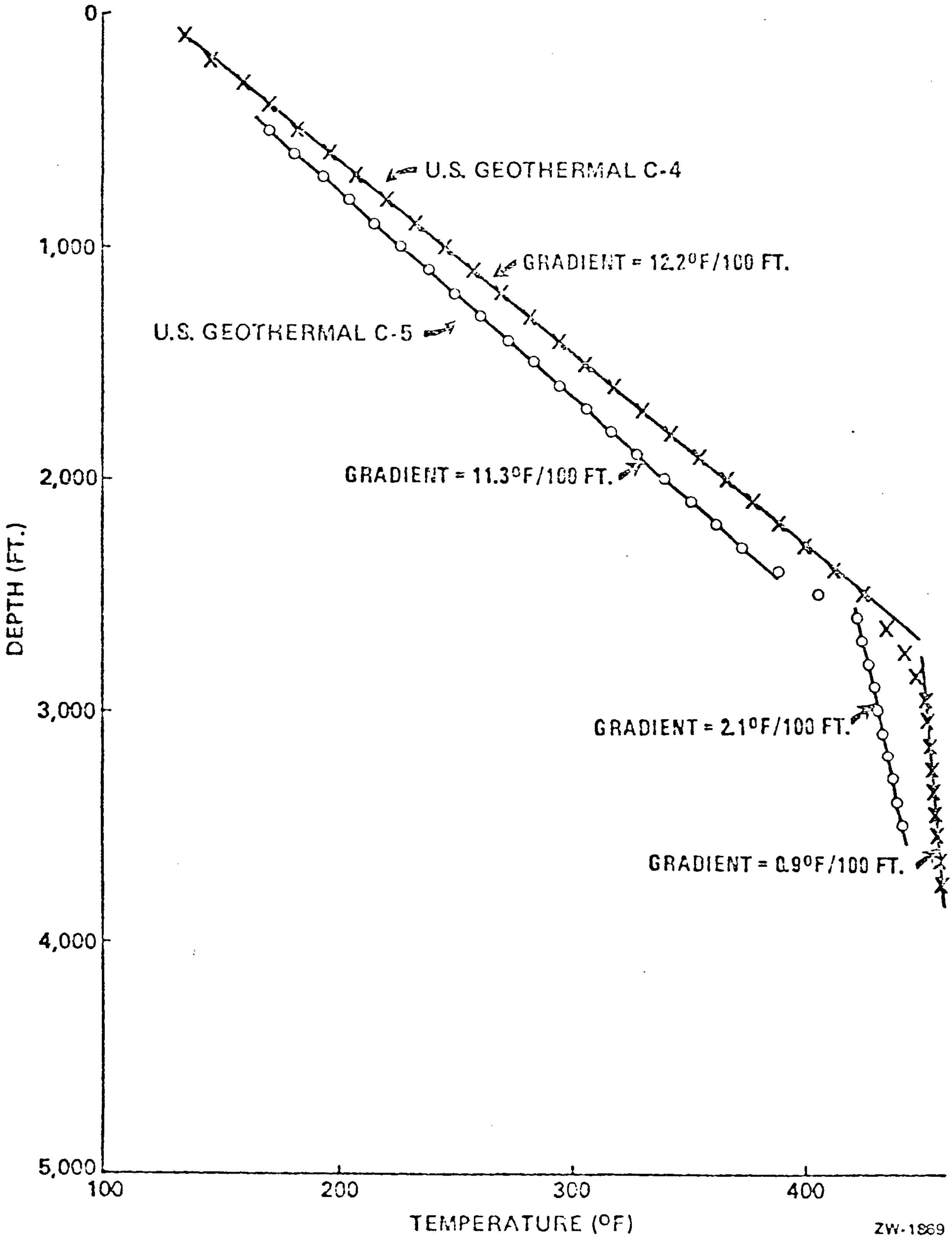

FIGURE 2
TEMPERATURE GRADIENTS
IN STEAM REFLUX ZONE