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ents on 'Theory of Heat Extraction From Fractured Hot Dry Rock' by A. C. Gringarten, P. A. Witherspoon, and Yuzo Ohnishi

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paper by *Gringarten et al.* [1975] points out the result that the extraction of geothermal energy efficient if the water passes through a multiple system than if the water passes through a single fracular, their results show that a given flow rate ong N fractures gives a higher outlet temperature of time t_0 than if the same amount of fluid flows single fracture.

to me, however, that their model is unnecessarily ed and hence the physical significance of the model partially obscured. For this reason I wish to show that the same results may be obtained by solving the equation for a single fracture and by treating the system as a number of N independent, vertical

ations for a single fracture, based on the same princias those of *Gringarten et al.* [1975], have been *Bodvarsson* [1969]. With the use of the same nota*Gringarten et al.* [1975] used, they are

$$\rho_W c_W Q(\partial T_W/\partial z) = 2K_R(\partial T_R/\partial x)|_{x=0} \qquad (1)$$

$$\partial^2 T_R/\partial x^2 = (1/a_R)(\partial T_R/\partial t) \qquad (2)$$

$$T_R(x, z, 0) = T_{R0} \qquad (3)$$

$$T_W(x, 0, t) = T_{W0} \qquad (4)$$

Q is the volume flow rate per meter of T_{R0} is the initial temperature of the formation, the temperature at which the water is injected into The solution to (1)-(4) can be found straightthe water temperature being given as

$$= T_{W0} + (T_{R0} - T_{W0})\ \mathrm{erf}\ \frac{K_R z}{c_W \rho_W Q(a_R t)^{1/2}} \qquad (5)$$

(5) shows that the initial temperature of the water fracture is T_{R0}, and that the outlet temperature of s slowly with increasing time. An important feathermal systems is exhibited by (5). For a given fracture height the ratio

$$(T_W(h, t) - T_{W0})/(T_{R0} - T_{W0}) \qquad (6)$$

al to $1/Q(t)^{1/2}$. In practice, a geothermal system erate effectively once the outlet temperature falls value. Therefore the ratio (6) is fixed by practical considerations, and (5) shows that the smaller the flow rate, the longer the geothermal system can operate effectively. Moreover, *Bodvarsson* [1970] has shown that a lower flow rate leads to a greater total yield of hot water. This result also follows from (5). If the ratio (6), a time of operation, and fracture height are chosen, (5) can be used to calculate the flow rate Q. With the use of the same numerical data as *Gringarten et al.* [1975] used and a time of 20 yr the result is $Q = 0.146$ cm^3/s per unit fracture length, which is nearly identical to the result of *Gringarten et al.* [1975]. To get the correct total flow through the geothermal system, one simply chooses a fracture length (say 1 km) and adds the results from a number of N independent fractures. To obtain the total flow assumed by *Gringarten et al.* [1975], N is equal to 10.

The reason why the independent fracture model gives the same results can be seen by consideration of the amount of conductive cooling of the hot rock which takes place over the time of energy extraction. The amount of conductive cooling at any horizontal distance L from a fracture is represented by the Fourier number $N_F = a_R t/L^2$. For the amount of conductive cooling to be small $N_F < \frac{1}{9}$. Therefore in order for the fractures to be considered thermally independent at a time t_0, the condition $L \geq 3(a_R t_0)^{1/2}$ must be satisfied where L is the separation between the fractures. For $t_0 = 20$ yr we obtain $L > 70$ m. This result is clearly substantiated by Figure 5 of *Gringarten et al.* [1975], since the outlet temperature shown is essentially independent of fracture separation for separations of greater than 80 m after a time of 20 yr. Moreover, there appears to be little thermal interference after 20 yr provided the separation is greater than 40 m. Consequently, the essential results of *Gringarten et al.* [1975] can be represented adequately by a model based on temperature conditions determined for a single fracture, the total geothermal system being represented by the sum of the results for N independent fractures.

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Reply

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We agree with R. P. Lowell that if one is interested only in those times when interference between fractures is negligible, as in our example, a simplified model for heat extraction that is obtained by combining independent single fractures would be sufficient. Lowell's equation (5) can actually be obtained from our equation (A18) by taking the limit as $x_e \to \infty$, which corresponds to the curve for $x_{ED} = \infty$ in Figure 3.

In a number of cases, however, it will be necessary to know the temperature drop after interference occurs. This would be the case, for example, when a new system of fractures is created to supplement the output from a previous system where temperatures have begun to drop and the hot waters from both systems are to be mixed before being utilized. In such a case the temperature cannot be obtained from Lowell's equation (5), and (A18) in our paper would have to be used.

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