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Radon modelling and the heat transfer surface area of the British hot dry rock geothermal reservoir

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Abstract. A simple thermal model is developed to evaluate the heat exchange surface area of a hot dry rock geothermal reservoir. This model, in conjunction with the Rn model of Andrews and coworkers, is applied to RH12/RH15 system of the British HDR reservoir. Results suggest that although the estimated Rn transfer surface area represents the actual swept surface area, it is between 25 and 45 times larger than the heat transfer surface area. The difference is explained as due to clustering of several fractures within a range of thermal interaction, over the duration of the circulation. It is also shown that the decline in the measured temperatures of circulation fluids since 1985 to the present is consistent with the heat exchange surface area going through a maximum in 1987.

Keywords. Radon modelling; heat transfer surface area; hot dry rock geothermal reservoir; thermal model; radon transfer surface.

1. Introduction

In recent years a significant effort in energy exploration is focussed on developing hot dry rock (HDR) geothermal reservoir systems. It is believed that HDR would offer the possibility of power generation in countries where sources of volcanic origin are non-existent.

Such resources contain large amounts of useful heat energy but do not spontaneously produce fluids (Smith *et al* 1973). These resources exist everywhere but at varying depths. The basic concept of extracting heat from the hot dry rocks comprises of drilling a pair of bore holes terminating several hundred meters apart and fracturing the rocks between them by hydraulic stimulation of naturally occurring fissures. The surface water is then circulated down the injection well, through the heat reservoir and finally up the production well to bring heat to the surface (Batcherlor 1978, 1982; Murphy *et al* 1981).

Two factors which determine the commercial viability of such systems are (i) an adequate surface area within the reservoir for the heat transfer which would control the life of the reservoir and (ii) the suitable hydraulic properties which would allow the heat to be extracted at a sufficient rate to achieve financial viability. Information on the fracture widths and the swept surface area of the reservoir is therefore essential in evaluating the performance of the HDR system.

Andrews *et al* (1986) demonstrated, for the first time, that the Rn content of the circulation water may be used in conjunction with the laboratory estimates of Rn flux from the reservoir rocks to evaluate the average fracture width and swept surface area of the HDR reservoir. Their model applied to RH12/RH15 doublet of the British HDR (Parker 1987), suggested the average fracture width of about 500 μm and the swept surface area of about 4 Mm^2 during the period between November 1985 and March 1986. Subsequently, more hydraulic treatment, like pressure oscillations and very high injection flow rates, was applied to the system and the effect of such treatments on the swept surface area and joint width was evaluated through the Rn model. Whereas the surface area grew steadily up to about 18 Mm^2 until early 1987, the average joint width reduced to about 400 μm. This is explained as a result of opening-up of several more flow channels with relatively smaller joint widths (Andrews and Hussain 1987; Andrews and Hussain, in preparation).

As stated earlier, estimates of the size of the system are essential for modelling the thermal performance and the life of the reservoir. Armstead and Tester (1987) suggested that the heat exchange surface area of a financially viable HDR must be at least 10 Mm^2. The mean Rn transfer surface area of the RH12/RH15 system was 11·8 Mm^2 in February 1988 (table 1). However, within 3 years of circulation, the production

Table 1. Heat exchange surface area of the doublet RH12/RH15 estimated by appropriately scaling down Rn model surface area during various tracer tests.

TT No.	Date	Cumulative flow time (days)	Flow rate (l/s)	Temperature (C)	Reservoir area (Mm^2) Rn	Reservoir area (Mm^2) Heat
6	181185	110	5·0	78	5·3	0·16
8	170286	201	5·7	76	7·1	0·25
10	240386	236	6·0	75	7·6	0·27
11	100486	253	6·6	75	6·1	0·26
13	240686	328	8·7	73	11·0	0·39
14	251186	482	6·0	69	11·1	0·26
15	061286	493	10·4	69	9·5	0·30
16	290187	547	11·2	68	14·0	0·49
18	270487	635	12·6	64	16·4	0·48
19	010987	762	13·6	62	18·0	0·43
20	140987	775	13·6	62	16·5	0·49
21	061087	797	13·7	60	16·1	0·50
22	131087	804	13·8	60	14·8	0·47
23	231087	814	13·8	60	12·8	0·42
24	041187	826	13·8	59	12·5	0·40
25	031287	855	13·9	58	10·7	0·33
29	160288	929	13·9	55	11·8	0·40

Note: The other values used in estimating the heat exhcange surface area (equation (12)) are the following

$k_r = 0{\cdot}00625\ \mathrm{cal\,cm^{-1}\,s^{-1}\,K^{-1}}$ (Sibbit and Dodson 1979)

$D = 0{\cdot}014\ \mathrm{cm^{-2}\,s^{-1}}$ (Batchelor 1981)

$C_w = 1\ \mathrm{cal\,g^{-1}\,K^{-1}}$

$\rho = 1\ \mathrm{g\,cm^{-3}}$

Values of k_r and D are at 100°C.

temperature dropped from 79°C to about 57°C. Such steep fall in temperature indicates a much smaller effective surface area of the reservoir for heat exchange than suggested by the Rn model.

This paper describes how the actual swept surface area estimated from the Rn model (Andrews *et al* 1986; Andrews and Hussain 1987) could be much larger than the heat transfer surface area. A simple thermal model is applied to discrete clusters of fractures and the temporal changes in the heat exchange surface area is evaluated based upon the temperature measurements of the return fluids. Results suggest that the experimental temperature profile is consistent with the heat exchange surface area going through a maximum over the history of circulation.

2. Radon transfer surfaces

^{222}Rn is a decay product of the 238-U series which is produced due to alpha decay of ^{226}Ra within rocks. Its noble gas character and the short half-life (3·8 days) makes it an ideal tracer in several geochemical investigations. The mechanisms of ^{222}Rn release from the rocks have been discussed by several workers (Wahl and Bonner 1951; Serdyukova and Kapitanov 1978; Tanner 1964, 1978). Recently, Sempirini (1985) has confirmed the original view held by Andrews and Wood (1972) relating the Rn-emanation rate from the rock to the square root of the grain size and concluded that more than 90% of the Rn release from the rocks is due to diffusion along crystal defects, grain boundaries or microfractures from greater depths below the emanating surface. This view is similar to that held by Rama and Moore (1984). The intensity of micro-fractures, their interconnectivity, the fluid filled in them and the distribution of ^{226}Ra in relation to the microfractures are the main factors controlling the Rn emanation rate from a rock. Andrews *et al* (1986) showed that Rn flux from the geometric surfaces of Carnmenellis granite (which also forms the reservoir RH12/RH15), increased with increasing cube edge and reached a limiting value of about 34 atom $m^{-2} s^{-1}$ for cube edges greater than 5 cm, when placed in water. The specimens for these experiments were saw cut in the shape of cubes. When the water was removed by prolonged drying and the cube was placed in air, a much higher limiting value of about 350 atom $m^{-2} s^{-1}$ was reached at a much larger cube edge of 29 cm. This observation is consistent with the diffusion theory of Rn transport from within the body of the rock to its surface.

The actual fracture system of an HDR reservoir may be idealized as shown in figure 1. The three vertical fracture types shown may be clusters of several vertical fractures, intersected by natural joints forming transverse connections. These intersections lead to several flow channels.

To interpret the inert tracer recovery data (Tester *et al* 1982) as well as Rn-modelling (Andrews *et al* 1986), it is assumed that the flow through these fractures can be simulated as plug-flow and therefore the time dispersion observed in the recovery of the tracer corresponds to the flow through gradually longer flow channels. The tracer residence time distribution curve (RTD) as shown in Andrews *et al* (1986) is given by

$$f(t) = QC(t)/m_p \tag{1}$$

where Q is the volumetric flow rate through the reservoir, $C(t)$ is the measured concentration of the tracer at any time t, following a pulse injection of the tracer at

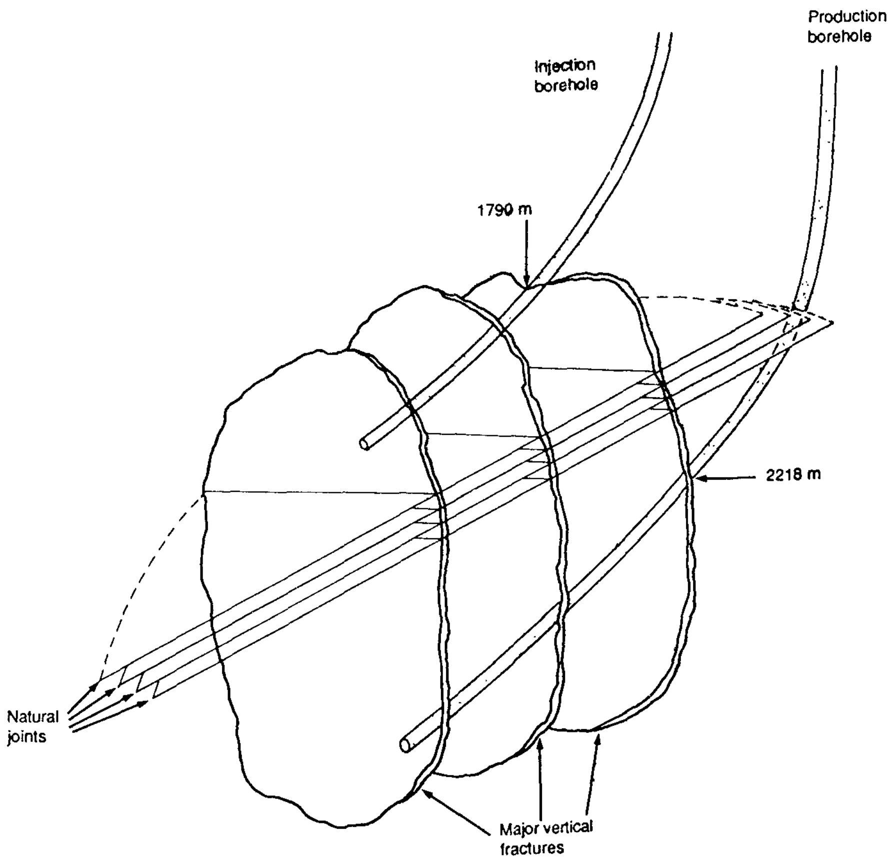

Figure 1. Cartoon showing the fracture geometry of the hot dry rock geothermal reservoir (RH12/RH15 system).

$t = 0$ and m_p is the mass of the tracer in the pulse (Kwakwa 1988). RTD curve is discretized representing a number of flow paths, the flow rate through each one is given by

$$q_i = Q \int_{t_{i-1}}^{t_i} f(t) \mathrm{d}t, \tag{2}$$

where t_{i-1} and t_i are the times chosen for discretization. The number of flow paths, n, must be kept large enough so that an adequate match to the RTD curve could be obtained. It is found through experience that $n \rangle = 10$ is a necessary condition for such a match. Fluid volume of each discrete flow path is given by

$$V_i = Q \int_{t_{i-1}}^{t_i} t f(t) \mathrm{d}t. \tag{3}$$

Assuming that the Rn flux is constant from all fracture surfaces and equals the limiting flux value measured from Carnmenellis granite in water medium, it is possible to estimate the average fracture width w of the flow channels in the reservoir from equation (4):

$$w = \frac{2F \sum_{i=1}^{n} q_i \{1 - \exp(-\lambda t_i)\}}{Q[\text{Rn}] - [\text{Rn}]_0 \sum_{i=1}^{n} q_i \exp(-\lambda t_i)}, \tag{4}$$

where F is the Rn flux from thick granite blocks, [Rn] and $[\text{Rn}]_0$ are the measured output and injection ^{222}Rn contents of the circulation waters and λ is the decay constant of ^{222}Rn. Full derivation details of equation (4) may be found in Andrews and Hussain (in preparation). Briefly, it could be obtained by modifying appropriately the model equation given by Andrews *et al* (1986) to account for the Rn contents of the injection waters.

3. Interacting fractures

The main objective of the HDR is to extract the stored heat energy of the geologic formations. The total amount of heat that can be 'mined' from the reservoir and hence the effective lifetime depends upon the distribution of flow through the volume of hot reservoir rock. Productivity will be maximized if the fluid is forced to sweep through a large number of well-distributed fractures with large surface area, rather than channel through just a few major joints.

The limiting value of Rn flux from Carnmenellis granite was obtained for cube edge exceeding 5 cm. Therefore the Rn model measures the surface area of all flowing fractures which are separated by over 5 cm and the total reservoir area is the sum of the surface areas of all such fractures. In contrast because the thermal diffusivity is high (0·014 $\text{cm}^2\,\text{s}^{-1}$, Batchelor 1981) a thermal disturbance would develop to a depth of 6 m below fracture surfaces during 3 years of circulation near the injection well. Near the production well, where the difference between fluid and rock temperature is smaller, the thermal disturbance may not penetrate at all. In general, in parts of the reservoir where the fracture frequency is high, several fractures may fall within the range of thermal interaction. Although they behave as separate fractures for Rn diffusion, they may be treated as a single fracture as far as heat transfer is concerned. Due to this difference in the "interaction depth" for Rn and heat, the area estimates are bound to be different. Depending upon the number of fractures which are within the range of thermal interaction at any reservoir position, a reduction factor to translate the Rn model area to the heat exchange surface area could be determined.

In the following, a simple thermal model is developed to estimate the heat exchange surface area of the reservoir from the observed temperature of the circulation fluid and appropriately reduced Rn model surface areas.

3.1 *Model development*

Heat is mobilized from rocks into fracture fluids mainly by conduction. Following Bodvarsson (1974), the heat flow equation (diffusion equation) for heat transfer from a thick rock formation could be written as:

$$\partial T/\partial t = D(\partial^2 T/\partial y^2), \tag{5}$$

where T is the temperature of the formation at any time t, D is the thermal diffusivity of the rock matrix and y is the distance increasing from the fracture surface into the thickness of the formation perpendicular to the fluid flow. One dimensional heat flow equation is valid provided within the extent of the reservoir the rock temperature is fairly uniform. On the fracture surface, the following boundary condition must be satisfied:

$$(Q\rho C_w/h)\partial T/\partial x|_{y=0} = (2k_r)\partial T/\partial y|_{y=0}, \tag{6}$$

where C_w is the specific heat of water, k_r is the thermal conductivity of the rock, $(Q\rho)$ is the mass flow rate of the fluid in the fracture (where ρ is the water density), h is the fracture height and x is the distance along the flow direction from the point of fluid injection. Equation (6) suggests that the thermal flux at the fluid injection point is solely due to the thermal conduction from within the formation. The other relevant conditions for solving (5) may be written down as:

$$T = T_0 \quad \text{for } x, y \rangle = 0 \quad \text{at } t = 0, \tag{7}$$

$$T = T_0 \quad \text{for } x, y \to \infty \quad \text{at } t > 0, \tag{8}$$

$$T = T_i \quad \text{for } x = y = 0 \quad \text{at } t > 0, \tag{9}$$

T_i is the temperature of the injection fluids. Solution of equation (5) subject to these initial and boundary conditions may be written as (Appendix-I):

$$T = (T_0 - T_i)\,\mathrm{erf}\,[\{y + (2k_r h/Q\rho C_w)x\}/2(Dt)^{1/2}] + T_i. \tag{10}$$

If the interwell separation between the injection and the production points is taken as the length of the fracture, L, then equation (10) for the temperature at the fracture surface ($y = 0$) may be re-written as

$$T = (T_0 - T_i)\,\mathrm{erf}\,[k_r A/2Q\rho C_w(Dt)^{1/2}] + T_i. \tag{11}$$

The heat transfer surface area ($A = 2hL$) may now be estimated using equation (11) at any time t since the circulation started for the measured value of the temperature of the circulation water and the hydraulic conditions of the reservoir. Applicability of (11) is subject to the condition that the whole reservoir could either be treated as a single fracture system or that the separation between different fractures is large enough so that the thermal disturbance due to the thermal drawdown from any fracture does not reach the adjacent one, or in other words the individual fractures remain thermally non-interacting. Typically over a period of five years of continuous circulation, thermal disturbance would reach a depth of about 10 m near the injection well ($D = 0{\cdot}014\,\mathrm{cm^2\,s^{-1}}$) and near the production well, the disturbance may not penetrate at all. For the case of n thermally non-interacting fractures, summation of (11) could be carried out such that the mean output temperature may be written as

$$T = (T_0 - T_i)\sum_{j=1}^{n}(q_j/Q)\,\mathrm{erf}\,[k_r A_j/2q_j\rho C_w(Dt)^{1/2}] + T_i. \tag{12}$$

Inherent in (12) is an assumption that the circulation fluid splits from a single injection point into different fractures and at the production end, all fracture flows get well mixed. Values of q_j/Q, which represent fractional flows through jth fracture, may be estimated from the inert tracer recovery curve as given by equation (2).

3.2 *Application to RH12/RH15 system*

Rn model envisaged the reservoir as consisting of n fracture types each defined by a characteristic length, width and the fluid transit time. The RTD curve was discretized into n equal time segments and the partial flow, q_i, from each quantile was related to its corresponding plug flow transit time, t_i. More recently, another approach of discretizing the RTD curve into equal flow segments has been shown to yield similar results (Hussain and Andrews, in preparation). In the former approach, the quantiles were selected to be equidistant in time whereas in the latter, the area under each quantile is equal. For the present purpose, the RTD curve during any tracer test is discretized into 10 equal flow quantiles. Rn model is applied to estimate the swept surface area contained in each flow quantile using equations (3) and (4). These areas together with the corresponding fractional flows are then substituted into equation (12) to estimate the temperature T of the return waters. (Values of other parameters used in these calculations are presented in the footnote of table 1).

It may be noted that the flow rates used in the Rn model are the actual measured flow rates at any time. However, for the thermal model they could not be used. This is because mobilization of Rn from rocks into water is essentially at a steady state with respect to its production in the rocks and thus the Rn flux at the fracture surfaces remains constant over times smaller than the half-life of ^{238}U. Mobilization of the stored heat never attains a steady state and therefore the heat flux at the fracture surfaces strongly depends upon the circulation history of the reservoir. As a first approximation, average flow rates were used in the thermal model which were calculated based on cumulative flows through the reservoir since the start of circulation. Flow values presented in table 1 are such averaged flow rates.

The calculated temperature using equation (12) during each tracer test (TT-6 to TT-29), was much in excess of the measured temperature at that time. This would be explained if the surface area obtained by Rn modelling were much larger than the area which is active in the heat exchange.

It has been mentioned before that the depth of interaction for Rn diffusion is within 5 cm in the reservoir rocks and since Rn is continuously generated within the rock this depth would remain fairly invariant with time. However, the depth of thermal interaction is a very sensitive function of time and typically over 5 years of continuous circulation it would reach a value of about 10 m near the injection well. The flow quantiles used in Rn model do not imply the existence of a single fracture but probably consist of many flowing fractures. Whereas these are non-interacting with respect to Rn, they could be sufficiently close together to be highly interacting thermally. If these fractures could be grouped into "clusters" such that each cluster may be regarded as thermally non-interacting, then the heat transport from the reservoir may be modelled in terms of such clusters of fractures.

Each flow quantile was therefore regarded as representing a single non-interacting thermal fracture but which included many conductive fractures that contributed to the Rn surface area. This is equivalent to selection of a reduction factor, f, to convert the Rn transfer surface area into a heat exchange surface area.

A value of f was selected and used to scale down the Rn model surface area for each flow quantile and these reduced areas were then substituted in (12) to calculate a new value of the production temperature. The process was repeated for modified values of f until agreement was obtained between the measured and calculated values of the production temperature. Results of these calculations during tracer tests 6 to

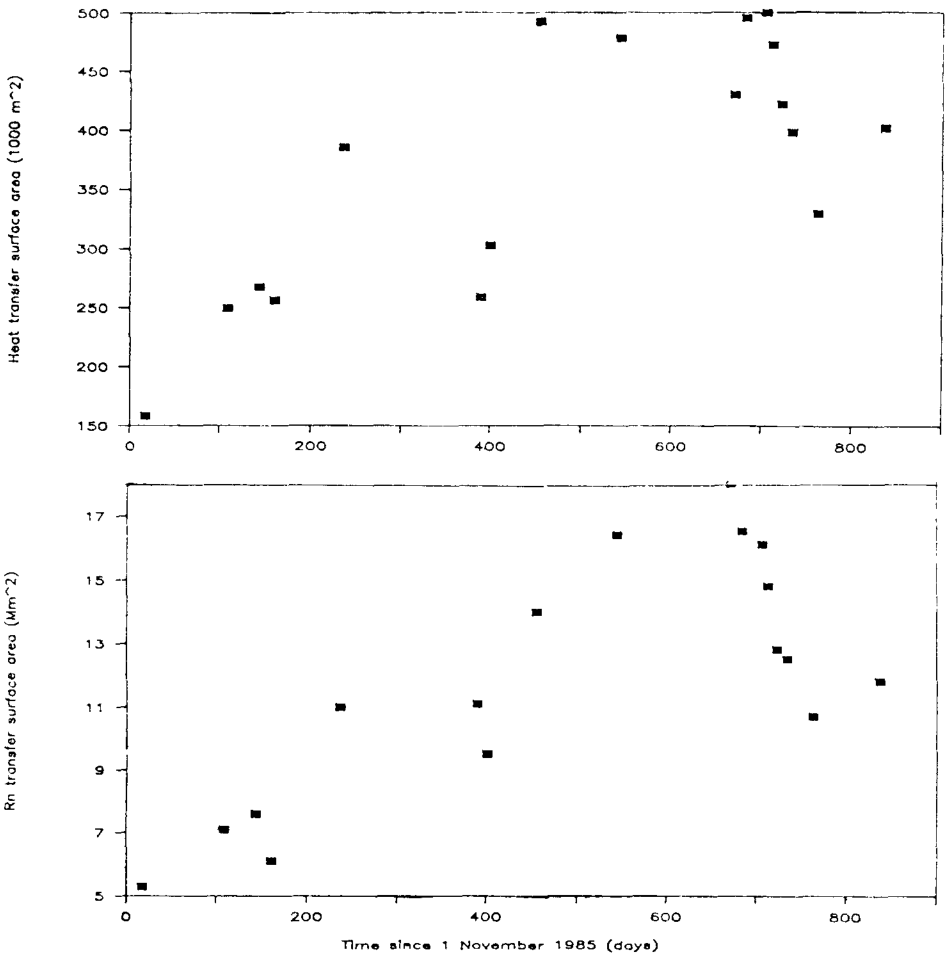

Figure 2. Heat transfer surface area calculated from present thermal modelling for the period between November 1985 and February 1988 (top). Bottom figure shows Rn model estimates of the surface area for the same duration.

29 are presented in table 1 and figure 2. It may be seen that in November 1985, the heat exchange surface area was about 160,000 m^2. It increased to about 500,000 m^2 until September 1987 and then declined to 330,000 m^2 until February 1988. There were no surface area measurements between April and September, 1987. It is probable that the heat transfer surface area peaked sometime before September. A parallel trend has been observed in the Rn model surface area estimates (table 1, figure 2).

The ratio of Rn to heat exchange surface area ($1/f$) varied between 25 and 45 and has a mean value of 34 +/− 5. Generally f^{-1} values were lower during the early phase of circulation and gradually increased to peak at around September 1987. Increase in f^{-1} could be a result of a further fracturing within the existing clusters and the data suggest that it occurred until just after the deployment of the downhole pump (Parker 1987) in August 1987. If the newly opened up flow channels within the existing clusters are responsible for the increase in f^{-1} value, it must also lead to an increase in the fluid transmissivity. The hydraulic data suggest that between November

1985 until April 1987, transmissivity of RH12/RH15 system had increased from $1{\cdot}1\,ls^{-1}\,MPa^{-1}$ to $1{\cdot}9\,ls^{-1}\,MPa^{-1}$. It then declined to $1{\cdot}6\,ls^{-1}\,MPa^{-1}$ until February 1988, essentially with increasing water losses.

The data suggest that, on average, each of the 10 flow quantiles can be regarded as a group or cluster of fractures which are thermally non-interacting with the clusters representing other flow quantiles. Within each group there exist about 30 equal area conductive fractures which contribute to Rn content of the production fluids, but since they are situated close together, all contact rock at the same temperature. In other words, they are situated within the thermal diffusion length of a few meters. It is also possible that the tortuosity of the flow paths, on a scale which is large compared with the Rn diffusion length of a few centimeters but insignificant compared with the thermal diffusion length, could contribute to the difference between the Rn and thermal surface areas.

4. Conclusion

The thermal model presented here is an idealized and therefore much too simplified model. While the non-interactive behaviour of different fractures and the clusters of fractures constituting the reservoir with respect to Rn diffusion could be little doubted, some of the clusters may indeed be thermally interactive. The effect of thermal interaction between the clusters, if any will tend to make the thermal area estimates presented here the upper limits. It is hard to speculate about the magnitudes of such changes because the actual distribution of fractures and their clusters is not known precisely. However, if the distribution of the clusters has not altered significantly over the time of study, then the relative variation of the estimated heat exchange surface area would seem to be real, which would suggest the heat exchange surface area of the reservoir has passed its peak value during early 1987.

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Appendix I

Equation to solve:

$$\partial T/\partial t = D(\partial^2 T/\partial y^2), \tag{A1}$$

where T is a function of time, t and the space variables x and y (see text). The condition of heat flux is given by:

$$(Q\rho C_w/h)\partial T/\partial x|_{y=0} = 2k_r \partial T/\partial y|_{y=0}, \tag{A2}$$

and the initial and other boundary conditions are:

$$T = T_0 \quad \text{for } x, y > = 0 \quad \text{at } t = 0, \tag{A3}$$

$$T = T_0 \quad \text{for } x, y \to \infty \quad \text{at } t > 0, \tag{A4}$$

$$T = T_i \quad \text{for } x = y = 0 \quad \text{at } t > 0. \tag{A5}$$

Re-arranging equation (A2)

$$\partial T/\partial x|_{y=0} = \alpha \partial T/\partial y|_{y=0}, \tag{A6}$$

where $\alpha = 2k_r h/Q\rho C_w$. Substituting $\theta = (T - T_0)/(T_i - T_0)$ and taking Laplace transform of equation (A1)

$$\partial^2 \bar{\theta}/\partial y^2 = (p/D)\bar{\theta}, \tag{A7}$$

where p is the Laplace variable. Solution of (A7) which is bounded at infinity may be written as:

$$\bar{\theta} = A(x, p) \exp\{-(p/D)^{1/2} y\}. \tag{A8}$$

To evaluate the function $A(x, p)$, derivatives of (A8) may be substituted into (A6) as follows

$$\partial A/\partial x \exp\{-(p/D)^{1/2} y\} = \alpha A\{-(p/D)^{1/2}\} \exp\{-(p/D)^{1/2} y\}. \tag{A9}$$

Re-arranging (A9)

$$\partial A/A = \alpha\{-(p/D)^{1/2}\} \partial x$$

or

$$A = B(p) \exp\{-(p/D)^{1/2} \alpha x\}. \tag{A10}$$

Substituting (A10) in (A8), it may be shown

$$\bar{\theta} = B(p) \exp\{-(p/D)^{1/2}(y + \alpha x)\}. \tag{A11}$$

Taking Laplace transform of (A5) after substituting for θ

$$\bar{\theta} = 1/p \quad \text{at } x = y = 0. \tag{A12}$$

Substituting $x = y = 0$ in (A11) and comparing with (A12), one obtains:

$$\bar{\theta} = 1/p \exp\{-(p/D)^{1/2}(y + \alpha x)\}. \tag{A13}$$

Inversion of (A13) yields:

$$\theta = \operatorname{erfc}[(y + \alpha x)/2(Dt)^{1/2}],$$

which after substitutions of θ and α gives the final solution:

$$T = (T_0 - T_i) \operatorname{erf}[\{y + (2k_r h/Q\rho C_w)x\}/2(Dt)^{1/2}] + T_i. \tag{A14}$$

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