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ENTHALPY TRANSIENTS IN FRACTURED TWO-PHASE GEOTHERMAL SYSTEMS

by

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ABSTRACT

Numerical modeling techniques are used to study the changes in flowing enthalpy of fluids produced from a well completed in a fractured two-phase geothermal reservoir. Complex interactions between different fracture and porous matrix parameters control the enthalpy transients. The results show that the flowing enthalpy is most sensitive to the characteristics of the relative permeability curves, the magnitude of the matrix permeability and the effective fracture porosity. Other parameters such as the thermal conductivity and fracture spacing also significantly affect the flowing enthalpy. In spite of the complex phenomena associated with enthalpy transients in fractured two-phase systems, it is possible to infer useful information about the producing geothermal reservoirs from field data.

INTRODUCTION

Many wells completed in high temperature (>200°C) fractured two-phase reservoirs show a significant increase in the enthalpy of the produced fluids (Stefansson and Steingrimsson, 1980; Grant and Glover, 1984; Bodvarsson et al., 1985). The observed wellhead enthalpy is commonly referred to as the flowing enthalpy (h_f) and differs significantly from that in-situ. It is defined as:

$$h_f = \frac{\dfrac{k_{r\ell} h_\ell}{\nu_\ell} + \dfrac{k_{rv} h_v}{\nu_v}}{\dfrac{k_{r\ell}}{\nu_\ell} + \dfrac{k_{rv}}{\nu_v}} \qquad (1)$$

The observed enthalpy transients have been analyzed using a porous media approach by Sorey et al. (1980), Bodvarsson et al. (1980), O'Sullivan (1981), and Bodvarsson (1984). They found that the rise in enthalpy depends in a complex manner on porosity, permeability, initial vapor saturation and relative permeabilities of the porous reservoir. For a constant rate fluid production from a porous system the enthalpy of the fluids will rise initially and then stabilize. Production under constant downhole pressure causes an increase in enthalpy at early times, followed by a gradual decrease (Bodvarsson, 1984).

Much less work has been done on enthalpy transients in fractured reservoirs. Grant and Glover (1984) analyzed enthalpy data from Broadlands well BR21 using a fracture model with impermeable matrix blocks (conduction effects). Pruess (1983a) studied the enthalpy of fluid recharging the fractures from the matrix and showed that it depends primarily upon the effective matrix permeability ($k\ k_r$). Other investigators have also studied the matrix fracture interaction for two-phase systems (Moench, 1978; Pinder et al., 1979; Moench and Denlinger, 1980).

The objectives of the present work are to identify the parameters that control the enthalpy rise in fractured porous media geothermal reservoirs. Numerical studies are conducted and the enthalpy behavior calculated for various combinations of important fracture and rock matrix parameters. Effects of different relative permeability parameters are also investigated.

APPROACH

The fractured nature of the reservoir is represented by a double-porosity model having three perpendicular sets of planar, parallel fractures of equal aperture and spacing. The "multiple interacting continua" method (MINC), developed by Pruess and Narasimhan (1982) is applied to model mass and heat transport in the fractured porous media. The two-phase nonisothermal reservoir code MULKOM (Pruess, 1983b) is used in the numerical simulations.

The numerical grid considers a single-layer radial reservoir of uniform thickness (1000 m) and infinite in radial extent. Thus, gravity effects are neglected. Adiabatic boundary conditions are assumed above and below the reservoir. All material properties and fracture geometry parameters are assumed to be uniform. The radius of the well is 0.1 m. The grid close to the well is very fine (Δr = 0.025 m), but increases logarithmically in size with radial distance.

SENSITIVITY STUDIES

The effect of changes in different matrix and fracture parameters on flowing enthalpy are studied. The computed enthalpies are downhole values; wellhead enthalpies are slightly lower because of conductive heat losses through the casing.

The relative permeability curves used in this study are shown in Figure 1. The "linear" relative permeability curves are similar to those used by Bodvarsson et al. (1984) for the Krafla field. The Corey curves (Corey, 1954) and the SGB curves (Sorey et al., 1980) are frequently used in numerical simulation of geothermal systems. For all curves the residual liquid saturation is assumed to be 0.4, and the residual steam saturation 0.05. The total kinematic mobilities ($k/\nu t$) for these curves is shown in Figure 2 as a function of saturation for a constant pressure of 9 MPa, the initital reservoir pressure. The total kinematic mobility is defined by:

$$\frac{k}{\nu_t} = k\left[\frac{k_{r\ell}}{\nu_\ell} + \frac{k_{rv}}{\nu_v}\right] \qquad (2)$$

The total kinematic mobility controls the total fluid flow for a given pressure gradient. Figure 2 shows that the mobility of the Corey curves is very low at intermediate saturation values, which is primarily due to the fact that the sum of the relative permeabilities for these curves is considerably less than unity. For both the linear curves and the SGB curves, $k_{r\ell} + k_{rv} = 1$ for all saturations, but due to the higher liquid mobility of the linear curves and the high liquid density (compared to that for vapor), the total mobility of the linear curves is higher than for the SGB curves.

Base Case

The parameters used in the base case are given in Table 1. In this case we use the linear relative permeability curves (see Fig. 1). The transient behavior of the flowing enthalpy and downhole pressure for the base case is shown in Figure 3. The figure shows that the well pressures decrease rapidly at early time because of the small mass capacity of the fractures. This causes extensive boiling within the fracture system and increases the vapor saturation, hence the enthalpy of the produced fluids. Later on, both the pressure drop and the enthalpy rise stabilize.

It is of interest to compare the pressure and enthalpy transients of the base case with those observed if no matrix blocks were present. This is shown by the dashed lines in Figure 3. When there is no rock matrix the enthalpy only rises to 1450 kJ/kg after 2 years, or 250 kJ/kg lower than that when the matrix is present. The pressure decreases only to about 6.1 MPa, compared to about 5.6 MPa. The smaller pressure drawdown in the case without rock matrix is related to the low enthalpy, high liquid saturation fluid flowing in the fractures. Because of the fluid's higher total kinematic mobility (Fig. 2), smaller pressure drawdowns are required to sustain the 50 kg/s production rate.

The enthalpy enhancement observed in the base case must be caused by the flow of high enthalpy fluids from the rock matrix to the fractures or alternatively conductive heat transfer from the matrix into the fractures. In this particular case the convective heat transfer from the rock matrix is larger than the conductive heat transfer, causing the rapid rise in the enthalpy. The later time gradual increase in enthalpy (about 76 J/day) is caused by conductive heat transfer between the matrix and the fractures. This gradual rise is not observed in a porous medium with homogeneous properties, if exploited at a constant mass rate. In that case the enthalpy stabilizes (Sorey et al., 1980; O'Sullivan, 1981).

Matrix Thermal Conductivity

The effect of matrix thermal conductivity (λ_m) on the flowing enthalpy is shown in Figure 4. When λ_m is equal to zero the flowing enthalpy is very low, because there is no enthalpy enhancement due to conduction. When realistic values of thermal conductivity are used, the enthalpy increases by 200 to 300 kJ/kg.

Matrix Permeability

The effective matrix permeability has large effects on the flowing enthalpy (Pruess, 1983a). The lower the matrix permeability, the higher the pressure gradient and consequently the temperature gradient in the rock matrix. This in turn enhances conductive heat transfer (see Fig. 5), which increases the enthalpy of fluids flowing from the rock matrix into the fractures. However, when the matrix permeability is very low, fluid flow is very small, and conduction dominates the enthalpy enhancement of the fluids flowing in the fractures.

The enthalpy enhancement is greatest in the case of an impermeable rock matrix; only conductive heat transfer occurs between the matrix and the fractures, so that the matrix blocks take a long time to cool down. Because of the low storage capacity of the fractures, the fluids must flow long distances through the fracture system, thus exposing the fracture fluids to a large surface area for conduction. Also, in the case of an impermeable rock matrix, the pressure (and temperature) drop in the fracture is more than in cases with permeable rock matrix, causing a larger temperature gradient for conductive heat flow.

Matrix Porosity

One of the most important parameters controlling enthalpy rise in porous medium flow is the matrix porosity (Sorey et al.,1980; Bodvarsson, 1984). However, we find that for the fractured systems studied here the influence of matrix porosity (ϕ_m) is rather small (Fig. 6). This parameter modifies the response time of the matrix to changes in the system, because it affects the thermal and fluid capacities. In the range of matrix porosities expected in fractured porous media systems, the effect on enthalpy is not too significant.

Fracture Spacing

For a given reservoir volume, the fracture spacing (D), i.e., the distance between the three sets of planar perpendicular fractures, is inversely proportional to the total surface area between the matrix and the fractures. Therefore, a decrease in fracture spacing favors conductive enhancement of the flowing enthalpy (see Fig. 7), and increases surface area for fluid flow between the rock matrix and the fractures.

Fracture Porosity

Here we define the fracture porosity (ϕ_f) as the volume fraction occupied by the fractures. Thus, the fracture porosity directly affects the fluid capacity of the fractures, that in turn controls the pressure decline, boiling rates and enthalpy rise in the fractures. As shown in Figure 8, fracture porosity has a significant effect on flowing enthalpy, it has in fact similar effects as the matrix porosity for porous medium flow.

Fracture Permeability-Thickness Product

The permeability-thickness product [$(kH)_f$] describes the ability of the fractures to transmit fluids. When it is low, the pressure drop around the well is large, intensifying the boiling and enthalpy enhancement. Figure 9 illustrates the effect of this fracture parameter on flowing enthalpy. In comparison to the fracture porosity, the effects of this parameter are rather small.

Relative Permeability Curves

As shown above (Fig. 2) the relative permability curves have a strong effect on the total kinematic mobility, and thus on the enthalpy and pressure transients of the system (Figs. 10 and 11). Because of the low total kinematic mobility in the case of the Corey curves, the reservoir system can not sustain the constant production rate of 50 kg/s; the downhole pressure drops immediately to unreasonably low levels.

As shown in Figure 10, the enthalpy is very sensitive to the relative permeability curves selected for the system. The flowing enthalpy rises much more for the SGB curves than for the linear curves because of the greater mobility of the steam phase for the SGB curves. In the base case we assume the same relative permeability curves for both the matrix and the fractures. However, one would expect that they would be quite different for the two media. We considered a case (Fig. 12) where the relative permeability curves in the fractures are changed from SGB to a type of "X-curves" (i.e., $k_{ri} = S_i$; $i = \ell,v$); SGB curves were kept for the rock matrix. This lowers the enthalpy rise considerably from what is calculated for the SGB curves only, because of the smaller vapor mobility for the X-curves. The enthalpy transients when X-curves are used in the fractures and linear curves in the matrix are similar to those of the base case.

DISCUSSION

From the above studies it is obvious that complex interactions between different fracture and matrix parameters control the enthalpy rise in fractured two-phase reservoirs. The enthalpy rise in the fractures themselves is superimposed by an enthalpy enhancement due to fluid flow and conductive heat transfer from the matrix to the fractures. The enthalpy rise in the fractures is primarily controlled by the fracture porosity, and to a lesser extent by the effective fracture permeabilty. This is similar to the porous medium case. The enthalpy of fluids recharging the fractures from the matrix, on the other hand, depends primarily upon the matrix permeability and thermal conductivity (Pruess, 1983a). If the matrix permeability is very low, the primary factors are the fracture spacing and the matrix thermal conductivity.

In most cases, the presence of the rock matrix will enhance the enthalpy of the fluids flowing in the fracture system to the well. However, when the matrix permeability is high, and the fracture porosity is low, the matrix will actually tend to reduce enthalpies.

The complexity of the enthalpy rise in two-phase fractured reservoirs, makes it impossible to deduce parameter values from observed enthalpy data. However, one can obtain qualitative information about the reservoir system. As an example let us consider the enthalpy data from Broadlands well BR21 (Grant and Glover, 1984). Figure 13 shows a rather constant low enthalpy at early times with a rapid rise after a few days. One can hypothesize from this data that fracture porosities and permeabilities are rather high around this well, causing the low early-time enthalpy. The late-time enthalpy rise suggests a rather tight rock matrix, with conduction primarily providing the enthalpy enhancement (Grant and Glover, 1984). However, some recharge from the rock matrix must be occurring because of linear pressure decline, even when the enthalpy is changing.

At other fields (e.g. Krafla, Iceland) the enthalpy exhibits a very rapid rise from practically that of pure liquid to that of saturated steam over a time period of 20-30 days (Stefansson and Steingrimsson, 1980). This behavior strongly suggests low fracture porosities and permeabilities and a very tight rock matrix.

For all the cases discussed previously, the reservoir is being exploited at a constant flow rate (50 kg/s). We conducted a few simulations assuming a constant pressure production at the well. The results obtained showed that after an initial rise in the enthalpy it remains practically constant. These results differ from those of porous media calculations, where a gradual decline follows the early rise in enthalpy (Bodvarsson, 1984). The reason for this difference is the conductive enthalpy enhancement observed in fractured reservoirs. This enhancement offsets the enthalpy decline observed in the porous media model.

CONCLUSIONS

From sensitivity studies of the effects of different parameters on the flowing enthalpy transients in a well completed in a fractured porous two-phase reservoir, the following conclusions can be made:

1. The enthalpy transients are strongly affected by conductive heat transfer between the rock matrix and the fracture fluids (Pruess, 1983a).

2. The characteristics of the relative permeability curves assumed for the porous matrix and the fractures have a very significant effect on enthalpy changes. Of primary importance is the

mobility of the vapor phase compared to the liquid phase.

3. The flowing enthalpy is also affected by many other fracture and matrix properties. Of primary importance are the matrix permeability, matrix thermal conductivity, fracture spacing, fracture permeability-thickness product and fracture porosity.

4. In contrast to porous media systems, the effect of matrix porosity on flowing enthalpy is small in fractured porous media.

5. The flowing enthalpy of the fluids produced from a fractured porous medium under constant bottomhole conditions stabilizes with time, as opposed to a gradual decline observed in porous media systems.

6. The fact that so many parameters affect the flowing enthalpy suggests that matching simulated and observed enthalpy transients will not result in a unique determination of fracture and rock matrix parameters. However, simultaneous matching of several wellhead and downhole parameters (e.g., enthalpy, flow rate, fluid composition and downhole pressure), will constrain the results and may ensure uniqueness of the interpretation.

ACKNOWLEGEMENTS

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NOMENCLATURE

D	fracture spacing, m
k	intrinsic permeability, m^2
k_r	relative permeability
k/νt	total kinematic mobility, s
h	fluid enthalpy, J/kg
P	downhole pressure, Pa
Q	mass flow rate, kg/s
S	saturation
S_r	residual (immobile) saturation
λ	thermal conductivity, W/m°C
ν	kinematic viscosity, m^2/s
φ	porosity

Subscripts

f	flowing, fracture
ℓ	liquid
m	matrix
o	initial
v	vapor

REFERENCES

Bodvarsson, G. S. 1984. Numerical studies of enthalpy and CO_2 transients in two-phase wells, Geothermal Resour. Council Trans., 8, 289-294.

Bodvarsson, G. S., O'Sullivan, M. J., and Tsang, C. F., 1980. The sensitivity of geothermal reservoir behavior to relative permeability parameters, Proc. Sixth Workshop on Geothermal Reservoir Engineering, Stanford University report SGP-TR-50, 224-237.

Bodvarsson, G. S., Pruess, K., Stefansson, V., Bjornsson, S., and Ojiambo, S. B., 1985. A summary of modeling studies of the East Olkaria geothermal field, Kenya, paper submitted to the 1985 International Symposium on Geothermal Energy.

Bodvarsson, G. S., Pruess, K., Stefansson, V., and Eliasson, E. T., 1984. The Krafla geothermal field, Iceland: 2. The natural state of the reservoir, Water Resour. Res., 20, 1531-1544.

Corey, A. T., 1954, The interrelation between gas and oil relative permeabilities, Producers Monthly, 19, Nov., 38-41.

Grant, M. A. and Glover, R. B., 1984. Two-phase heat and mass transfer experiment at well BR21 Broadlands, Geothermics, 13, 193-213.

Moench, A. F., 1978. The effect of thermal conduction upon pressure drawdown and buildup in fissured, vapor-dominated reservoirs, Proc. Fourth Workshop on Geothermal Reservoir Engineering, Stanford University report SGP-TR-30, 112-117.

Moench, A. F. and Denlinger, R., 1980. Fissure-block model for transient pressure analysis in geothermal steam reservoirs, Proc. Sixth Workshop on Geothermal Reservoir Engineering, Stanford University report SGP-TR-50, 178-187.

O'Sullivan, M. J., 1981. A similarity method for geothermal well test analysis, Water Resour. Res., 17, 390-398.

Pinder, G. F., Ramey, H. J., Shapiro, A., and Abriola, L., 1979. Block response to reinjection in a fractured geothermal reservoir, Proc. Fifth Workshop on Geothermal Reservoir Engineering, Stanford University report SGP-TR-40, 189-196.

Pruess, K., 1983a. Heat transfer in fractured geothermal reservoirs with boiling, Water Resour. Res., 19, 201-208.

Pruess, K., 1983b. Development of the general purpose simulator MULKOM, in 1982 Annual Report, Earth Sciences Division, Lawrence Berkeley Laboratory report LBL-15500, 133-134.

Pruess, K. and Narasimhan, T. N., 1982. On fluid reserves and the production of superheated steam from fractured, vapor-dominated geothermal reservoirs, Jour. Geophys. Res., 87, 9329-9339.

Sorey, M. J., Grant, M. A., and Bradford, E., 1980. Nonlinear effects in two-phase flow to wells in geothermal reservoirs, Water Resour. Res., 16, 767-777.

Stefansson, V., and Steingrimsson, B., 1980. Production characteristics of wells tapping two-phase reservoir at Krafla and Namafjall, Proc. Sixth Workshop on Geothermal Reservoir Engineering, Stanford University report SGP-TR-50, 49-59.

Table 1. Parameters used in the base case.

Matrix properties	
Rock grain density	2,650 kg/m^3
Rock specific heat	1,000 J/kg°C
Rock thermal conductivity (λ_m)	2 W/m°C
Porosity (ϕ_m)	0.05
Permeability (k_m)	5 x 10^{-3} md
Relative permeability curves	linear
Fracture properties	
Spacing (D)	100 m
Equivalent continuum permeability-thickness product [(kH)$_f$]	5 Dm
Fracture porosity (ϕ_f)	0.01
Relative permeability curves	linear
Thermal conductivity	2 W/m°C
Initial conditions	
Downhole pressure (P_o)	9 MPa
Steam saturation (S_{vo})	0.10
Temperature (T_o)	303.3°C
Flowing enthalpy (h_{fo})	1407 kJ/kg
Well Production Rate (constant)	50 kg/s

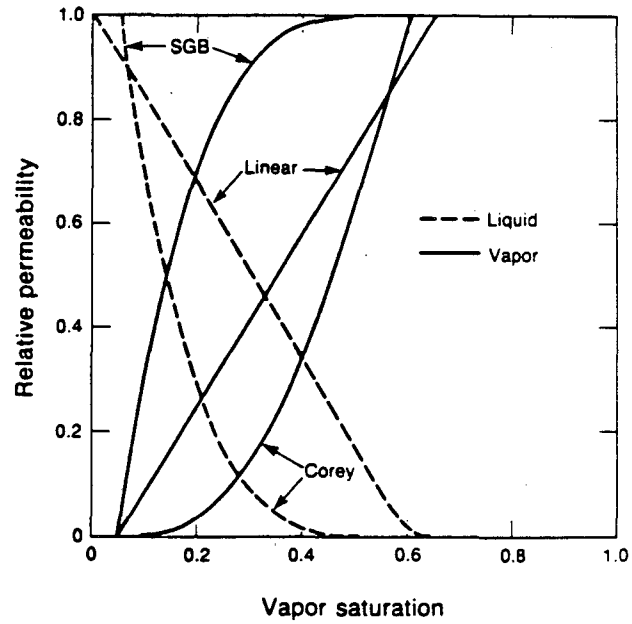

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Figure 1. Relative permeability curves used in this study (S_{rv} = 0.4, $S_{r\ell}$ = 0.05).

Table 2. Parameters varied in the sensitivity studies.

Parameter	Base Case	Other Cases
Matrix porosity (ϕ_m)	0.05	0.01, 0.10
Matrix permeability (k_m), md	5 x 10^{-3}	5 x 10^{-2}, 5 x 10^{-4}, 0
Matrix thermal conductivity (λ_m), W/m°C	2	4, 0
Matrix relative permeability curves	Linear	SGB
Fracture spacing (D), m	100	20, 500
Fracture porosty (ϕ_f)	0.01	0.0025, 0.02
Fracture permeability-thickness product [(kH)$_f$], Dm	5	10
Initial vapor saturation (S_{vo})	.10	.20
Mass flow rate (Q), kg/s	50	Q = f(P)

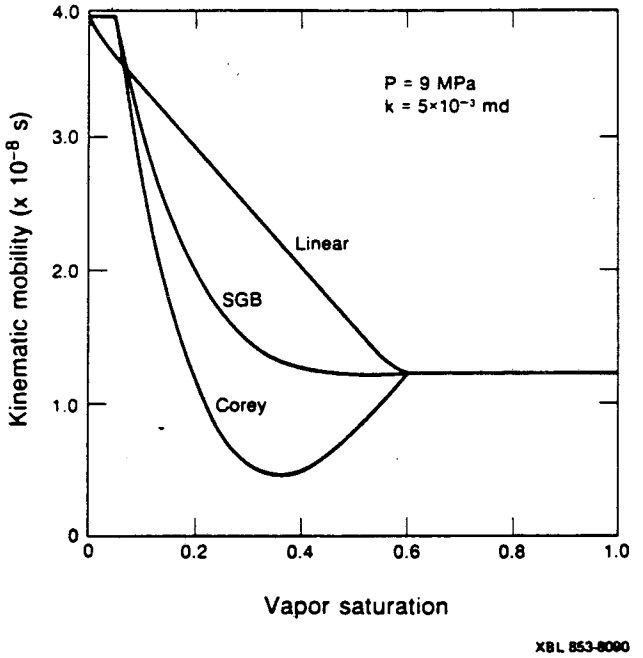

Figure 2. Total kinematic mobility curves for the relative permeability curves shown on Figure 1.

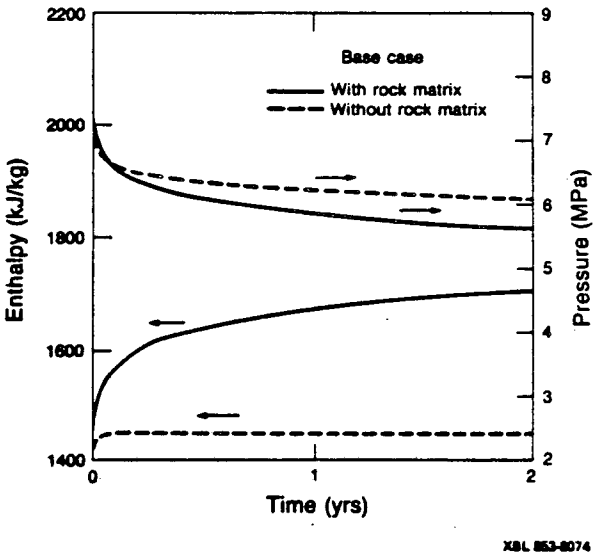

Figure 3. Flowing enthalpy and downhole pressure transients for the base case.

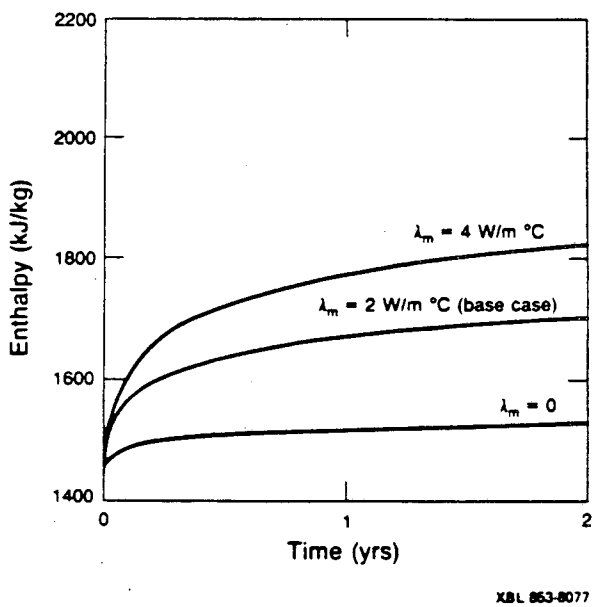

Figure 4. Effect of matrix thermal conductivity on flowing enthalpy transients.

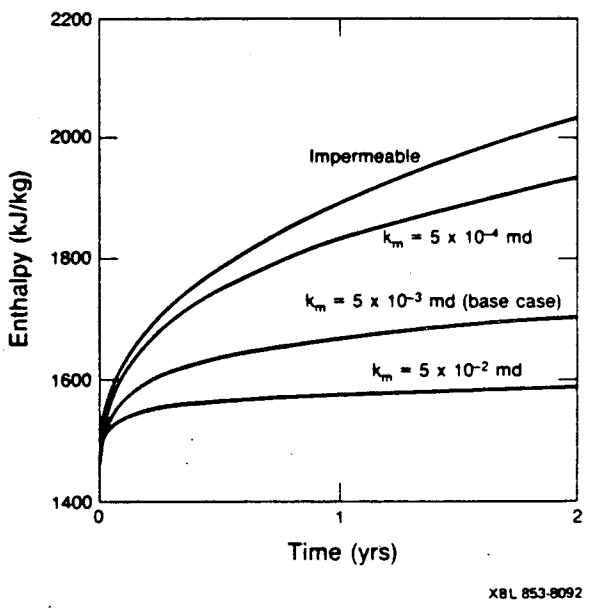

Figure 5. Effect of matrix permeability on flowing enthalpy transients.

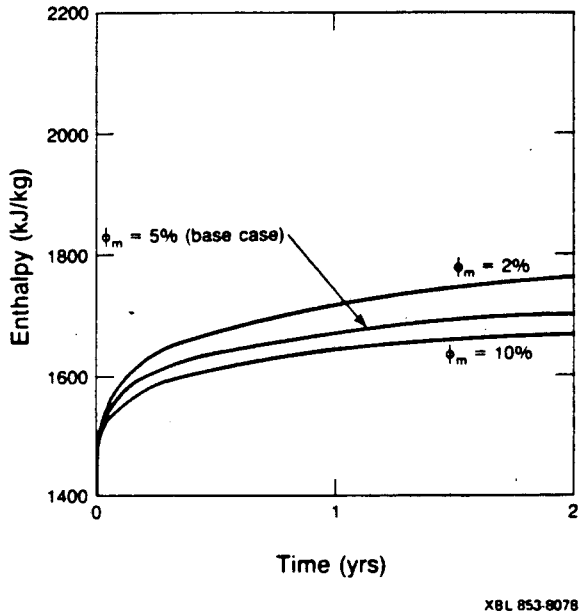

Figure 6. Effect of matrix porosity on flowing enthalpy transients.

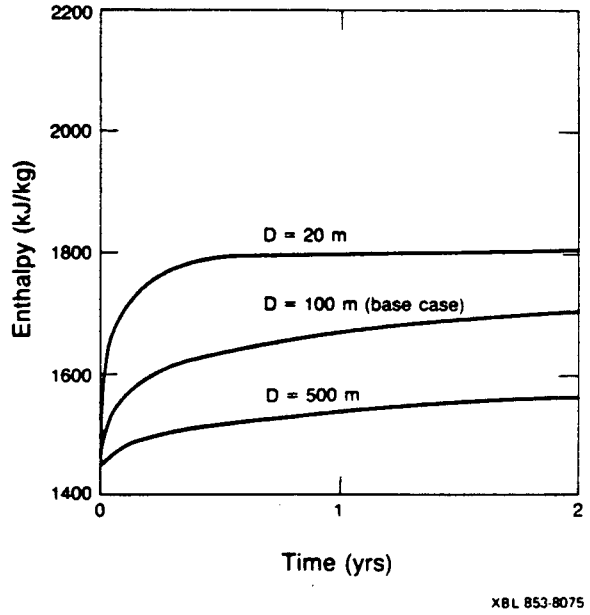

Figure 7. Effect of fracture spacing on flowing enthalpy transients.

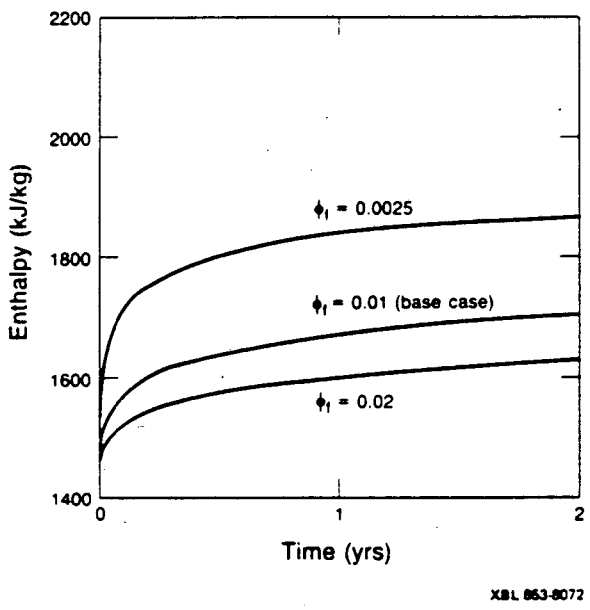

Figure 8. Effect of fracture porosity on flowing enthalpy transients.

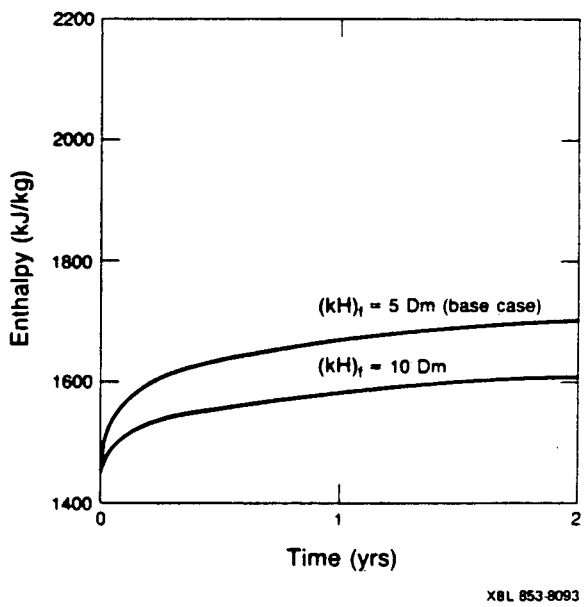

Figure 9. Effect of fracture permeability-thickness product on flowing enthalpy transients.

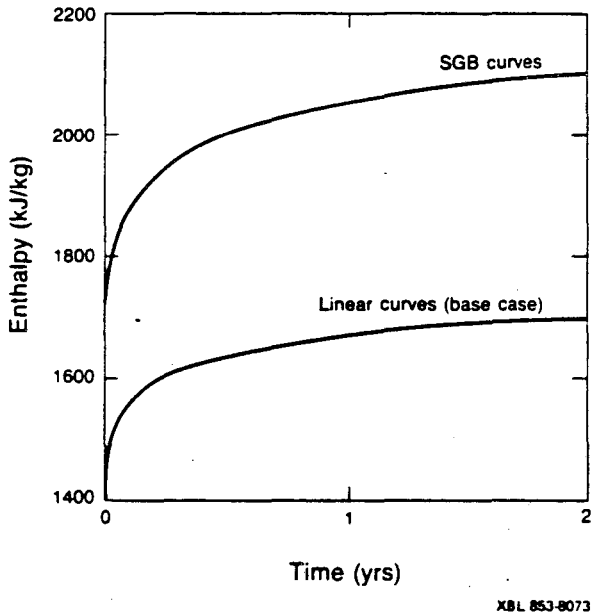

Figure 10. Effect of relative permeability curves on flowing enthalpy (the initial enthalpy for the SGB (Sorey et al., 1980) curves is 1536 kJ/kg).

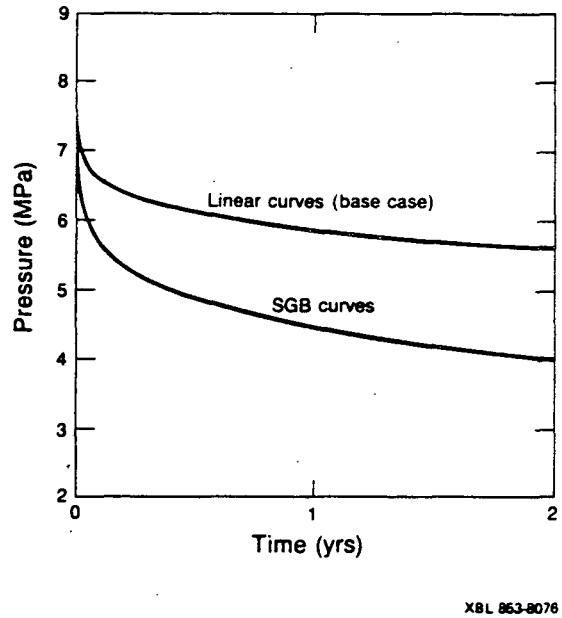

Figure 11. The effect of relative permeability curve on downhole pressure.

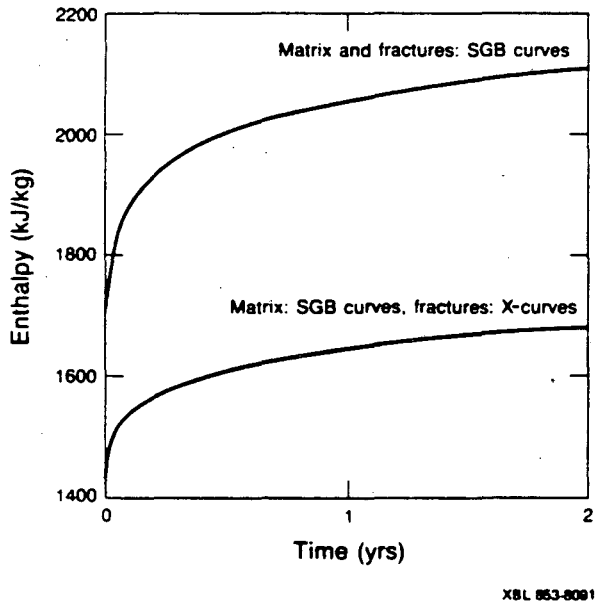

Figure 12. Effect of using different relative permeability curves in the matrix and in the fractures on flowing enthalpy (the initial enthalpy for the X-curves is 1409 kJ/kg).

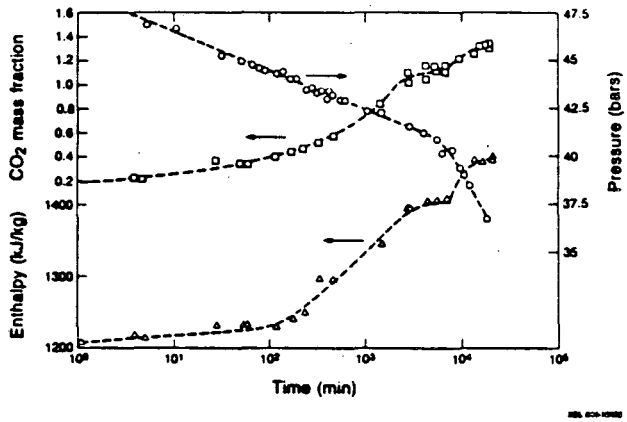

Figure 13. Enthalpy, downhole pressure and CO_2 content variations with time for Broadlands well BR21 (after Grant and Glover, 1984).

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