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ENERGY RECOVERY BY WATER INJECTION

P.A. Witherspoon, G.S. Bodvarsson, K.Pruess, and C.F. Tsang

July 1982

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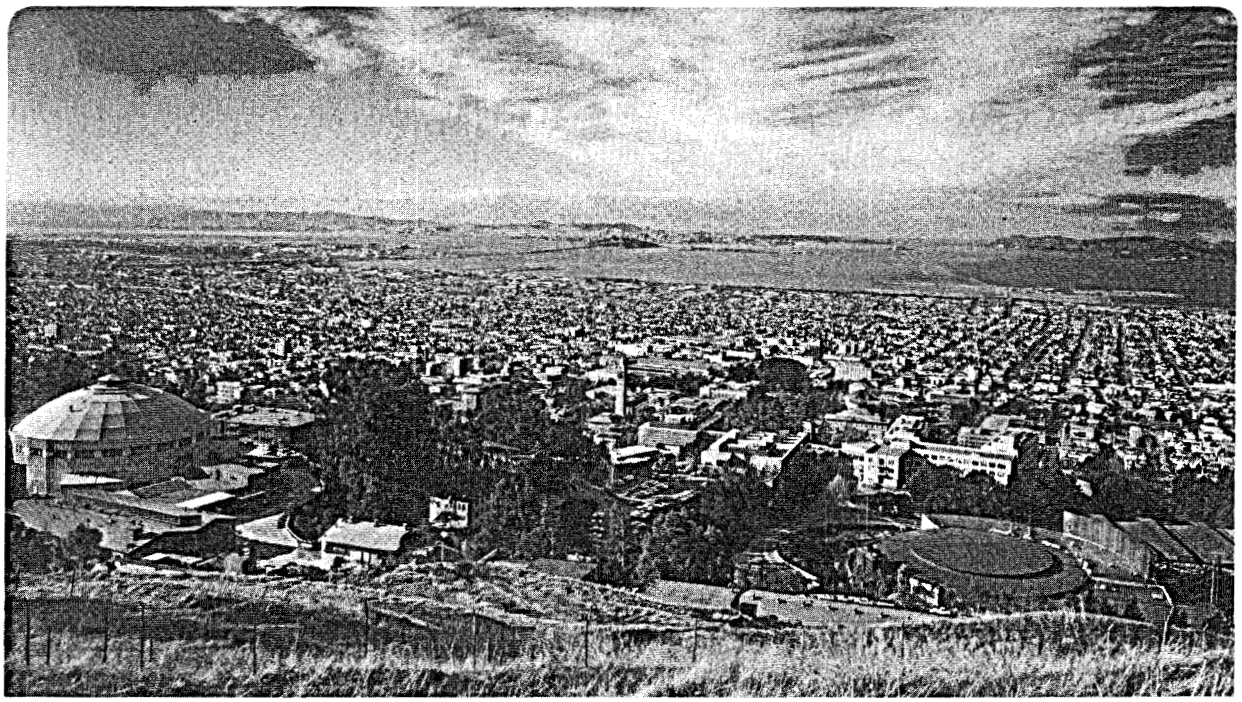

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ENERGY RECOVERY BY WATER INJECTION

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ABSTRACT

It is well established that reinjection of spent fluids can greatly enhance the recoverable energy from geothermal systems. There is, however, concern among field developers that the cold water may cause premature thermal breakthrough at production wells and consequently reduce the enthalpy of the produced fluids. A number of studies have addressed this problem, but these have generally considered porous media type reservoirs, although most geothermal reservoirs are extensively fractured. In this paper several analytical and numerical studies that address injection and thermal breakthrough in fractured geothermal reservoirs will be described. The results show that excellent thermal sweeps can be achieved in fractured reservoirs, and that premature cold water breakthrough can be avoided if the injection wells are appropriately located.

INTRODUCTION

Reinjection of geothermal wastewater is gradually becoming a preferred means of waste disposal. At present, continuous reinjection is practiced at The Geysers, California; Ahuachapan, El Salvador; Mak Ban, Philippines; and five Japanese geothermal fields (Otake, Onuma, Onikobe, Hatchobaru, and Kakkonda). Small-scale reinjection tests have been reported at a number of geothermal fields, e.g., Baca, New Mexico; East Mesa, California; Larderello, Italy; Cerro Prieto, Mexico; Broadlands, New Zealand; and Tongonan, Philippines. The increasing interest in reinjection undoubtedly results from growing environmental concerns regarding toxic minerals (e.g., boron, arsenic) present in geothermal wastewater.

A problem which may arise in reinjection is premature breakthrough of colder water in the production region, which can drastically reduce the enthalpy of the produced fluids. The movement of the cold water (thermal front) in porous media type reservoirs is fairly well known from theoretical studies by various investigators (Kasameyer, 1976; Schroeder et al., 1980). However, fluid movement in most geothermal reservoirs (except those in the Imperial Valley) is controlled by fractures, which is a more complicated situation. It appears possible that the cold water will advance very rapidly through the fractures and break through prematurely at the production wells.

In the present paper we use analytical and numerical methods to study injection into fractured geothermal reservoirs. In the analytical approach we investigate how the cold water front advances in fracture systems of equally spaced horizontal fractures, and in naturally fractured reservoirs. Mathematical expressions are derived which can be used to design proper spacings between production and injection wells. Subsequently we describe a new practical method for numerical modeling of mass and heat transfer in naturally fractured reservoirs. The application of the method to injection studies is illustrated by considering different well configurations such as a doublet and a five-spot pattern.

ANALYTICAL STUDIES

Analytical methods are employed in studies of the cold water front movement during injection into fractured reservoirs. Two basic cases are considered, namely, a reservoir containing equally spaced horizontal fractures and a naturally fractured reservoir (i.e. both horizontal and vertical fractures are present). In the following discussion the theory of the horizontal fracture case is given in detail and some important results are presented for the naturally fractured reservoir case. Comparison between results of the two cases is also included. Detailed analysis of the two cases are given by Bodvarsson and Tsang (1982) and Bodvarsson and Lai (1982).

BASIC MODEL - HORIZONTAL FRACTURES

The physical model consists of an injection well that fully penetrates a reservoir with n equally spaced horizontal fractures (Fig. 1). The fractures are all identical, having a constant aperture b, and extending to infinity. The injection rate, q_t, is assumed to be constant, and the same fluid mass flow rate, q, enters each fracture ($q_t = n.q$). Gravity effects are neglected, and, because of symmetry, only the basic section specified in Figure 1 need be considered. The rock matrix is assumed to be impermeable, hence only the effects of thermal conductions are present. In the numerical studies (below), most of the assumptions employed in the analytical work are relaxed, and cases in which the rock matrix is permeable are considered.

Figure 2 is a schematic diagram of the basic model considered in the analytical study. Besides the general assumptions discussed above, the following approximations are made:

1. The flow in the fracture is steady and purely radial, with the well located at $r = 0$. The fracture aperture b is at an elevation of $z = 0$ with the rock matrix extending vertically to $z = \pm D$.

2. Thermal equilibrium between the fluid and the solids in the fracture is instantaneous. Furthermore, horizontal heat conduction in the fracture is neglected, and temperature in the vertical direction is assumed uniform (infinite vertical thermal conductivity).

3. The rock matrix above and below the fracture is impermeable. Horizontal conduction is neglected, and the vertical thermal conductivity is finite. Heat flow boundaries at $z = \pm D$ are assumed to be "no flow".

The differential equation governing the fluid temperature in the fracture can be derived by performing an energy balance on a control volume in the fracture. The derivation is similar to those reported by Lauwerier (1955), Bodvarsson (1969), and Gringarten et al. (1975), and will not be discussed here.

RESULTS

A solution for the temperature field can be obtained in the Laplace domain. Inversion from the Laplace domain to real space can not be done analytically, but requires a numerical inverter. The inverter used here was developed by Stehfest (1970), and for this problem it gave results accurate within 0.7%.

Figures 3 and 4 show the thermal diffusion from the fracture to the rock matrix for $\theta < 10^{-2}$ and $\theta > 100$, respectively. The dimensionless parameter θ represents the ratio of the energy content of the fracture to that of the rock. Low values of θ indicate negligible energy content in the fracture, and large values correspond to negligible energy content in the rock. For the problem at hand, θ will most likely be less than 10^{-2} for all practical purposes.

In Figures 3 and 4, each plotted line indicates the location of the thermal front at the specified dimensionless time. Here the thermal front is defined as the locus of points with temperatures intermediate between injection temperature and original reservoir temperature. The figures show that during cold water injection into the fractured rock, the thermal front will advance very rapidly along the fracture at early times, as only a small amount of heat is obtained from the rock. Later on, however, as the available surface area for heat transfer from the rock to the fracture increases, the rate of advancement of the thermal front along the fracture decreases, and the cold front starts to penetrate the rock matrix. Eventually, the thermal front in the rock matrix catches up with the thermal front in the fracture at a time corresponding to $\tau \approx 1.0$, and after that a uniform energy-sweeping mechanism will prevail.

The rate of cold water advancement along the fracture is of course one of the major concerns in the present problem. In Figure 5, type curves representing the movement of the thermal front in the fracture ($\eta = 0$) are given for various values of θ. At early times, the effects of heat conduction to caprock and bedrock are negligible; consequently, a pistonlike displacement occurs in the fracture. In this case the advancement of the thermal front along the fracture is controlled by t/r^2. At intermediate times, the rock will start to conduct significant amounts of heat to the fracture and consequently slow the advancement of the cold water front along the fracture. This is evident in Figure 5 by the convergence of each θ curve to the mother curve ($\theta = 0$). The slope of the curve indicates that time t is proportional to the radial distance to the fourth power. This indicates how heat conduction effectively retards the advancement of the thermal front along the fracture.

As is evident in Figure 5, the θ dependence no longer exists at large dimensionless times, so that the relation between the dimensionless time τ and the dimensionless distance ξ becomes simply

$$\tau = \xi, \tag{1}$$

Equation (1) holds for both the fracture and the rock matrix.

The transition from the intermediate-time solution to the long-time solution occurs when the conductive heat flow from the rock matrix to the fracture becomes affected by the no-heat-flow boundary condition at $\eta = 1$ (insulated at $z = D$). The transition occurs at the time and location given by the following equation:

$$\tau = \xi = \frac{(2 + \theta)^2}{4.396} . \tag{2}$$

Equation (2) can be written in terms of physical parameters to yield:

$$t_c = \frac{2\rho_r C_r D^2}{4.396\lambda} \tag{3}$$

and

$$r_c = \left(\frac{2\rho_w C_w qD}{4.396\pi\lambda}\right)^{1/2} \tag{4}$$

where t_c and r_c denote the time and radial distance from the injection well, where uniform energy sweep is achieved.

NATURALLY FRACTURED RESERVOIRS

Similar analysis were carried out for the case of naturally fractured reservoirs.

The model used, shown in Figure 6, consists of rectangular matrix blocks bounded by three sets of orthogonal fractures. Steady state fluid flow is assumed in the fractures, but fully transient conductive heat transfer between the impermeable rock matrix and the fractures is taken into account. Thus, the cold water will flow from the injection well into the fracture network, and as it moves away from the well, it will gradually be heated by heat transfer from adjacent matrix blocks.

The equation for conductive heat transfer between matrix blocks and fractures is derived for the basic element shown in Figure 7, representing 1/6 of a single matrix block (cube). Assuming that thermal gradients are much smaller within the fracture network than in the rock matrix, heat flux at each point in the matrix is approximated as occurring only in the direction of the nearest fracture. This yields a one-dimensional approximation to the heat conduction in the matrix, the accuracy of which has been verified by comparison with the 3-dimensional Fourier-series solution (Lai, Bodvarsson, and Pruess, 1982). This approach is quite similar to the "multiple interacting continua" method (MINC) for numerical modeling of heat and fluid flow in fractured porous media (see below).

The results of our studies of injection into naturally fractured reservoirs are similar to the ones obtained for the horizontal fracture case. However, the time of uniform energy sweep conditions and its radial distance from the injection well is different. Approximate comparison between the two cases yields:

$$(r_c)_H \approx 2.0 \times (r_c)_{HV} \tag{5}$$

and

$$(t_c)_H \approx 4.0 \times (t_c)_{HV} \tag{6}$$

where the subscripts H and HV refer to the cases of horizontally fractured and naturally fractured reservoirs, respectively. Equations 5 and 6 show that conditions of uniform energy sweep occur at a time and radial distance that are considerably shorter in the case of naturally fractured reservoirs. When both vertical and horizontal fractures are present, there is a much greater surface area for heat transfer between fractures and rock matrix than in the case of horizontal fractures only. It is important to note that in both cases, the time and radial distance of the uniform energy sweep conditions are independent of the fracture aperture.

EXAMPLE

Let us consider an injection well in a naturally fractured reservoir using the parameters shown in Table 1. If the average fracture spacing is not known the following expressions can be calculated:

$$r_c = 2.6 \times D \text{ (meters)} \tag{7}$$

$$t_c = 0.01 \times D^2 \text{ (years)}, \tag{8}$$

where D is the fracture spacing. Thus, for an average fracture spacing of 50 m, uniform energy sweep conditions will prevail 130 m away from the well after 25 years of injection.

NUMERICAL STUDIES-MULTIPLE INTERACTING CONTINUA

We shall now discuss a numerical method for modeling fluid and heat flow in naturally fractured rock masses. The method of "multiple interacting continua" (MINC) treats the flow in fractures, rock matrix, and between fractures and rock matrix by numerical methods without invoking approximations often made in analytical and semi-analytical methods. It is therefore quite general and applicable to complex systems such as multiphase fluids with large and variable compressibility, phase transitions with latent heat effects, as well as transient fluid and heat flow in both rock matrix and fractures. Also, the MINC-description is applicable to reservoirs with irregular and statistical fracture distributions, although the calculations reported below were made for highly idealized fracture patterns. A detailed account of the foundations of the MINC-method has been given by Pruess and Narasimhan (1982). In the present paper we shall give a brief summary of the methodology, followed by illustrative applications for geothermal injection problems.

In order to numerically model flow processes in geothermal reservoirs (or, for that matter, in any subsurface flow systems), it is necessary to partition the system under study into a number of volume elements V_n ($n = 1, 2, \ldots, N$). Then the appropriate conservation equations for mass, energy, and momentum can be written down for each volume element. These equations hold true irrespective of size, shape, heterogeneities etc. of the volume elements V_n. This geometric flexibility can be most fully exploited within an integral finite difference formulation which is locally one-dimensional, avoiding any reference to a global coordinate system (Edwards, 1972). However, the conservation equations in integral finite difference form are useful only if the allowable partitions V_n ($n = 1, \ldots, N$) are suitably restricted on the basis of geometric and thermodynamic considerations. Indeed, for practical applications we need to be able to relate fluid and heat flow between volume elements to the accumulation of fluid and heat within volume elements. Fluid and heat flow are driven by gradients of pressure and temperature, respectively, and these can be expressed in terms of average values of thermodynamic variables if (and only if) there is approximate thermodynamic equilibrium within each element. In porous media, this requirement will be satisfied for any suitably "small" subregion, as thermodynamic conditions generally vary continuously and smoothly with position. The situation can be quite different in fractured media, where changes in thermodynamic conditions as a consequence of cold water injection may propagate rapidly in the fracture network, while migrating only slowly into the rock matrix. Thus, thermodynamic conditions may vary rapidly as a function of position in the vicinity of the fractures. Based on the different response times, the MINC-method makes the approximation that thermodynamic conditions in the matrix depend locally only upon the distance from the nearest fracture.

For the idealized fracture distribution shown in Figure 6, the requirement of approximate thermodynamic equilibrium then gives rise to a computational mesh as shown in Figure 7. The matrix is partitioned into a series of nested volume elements, defined according to the distance from the nearest fracture. Modeling of fluid and heat flow in such a system of interacting continua is straight-forward within an integral finite difference formulation. The matrix-fracture interaction is described in purely geometrical terms, and the relevant geometric quantities, i.e. element volumes, interface areas, and nodal distances, can be easily obtained in closed form. The pertinent expressions are given by Pruess and Narasimhan (1982), who also discuss a generalization of the model to grid blocks of arbitrary size or shape. A further generalization to statistical fracture distribution has been developed by Pruess and Karasaki (1982), who use Monte Carlo techniques to represent the "proximity" of the matrix rock to the fractures.

The calculations reported below use the idealized fracture distribution previously considered by Pruess and Narasimhan (1982). A preprocessor program has been written which generates the geometric parameters of the computational mesh. The geothermal reservoir simulations were carried out with LBL's two-phase simulators SHAFT79 and MULKOM, which feature an accurate representation of the thermophysical properties of water substance, and a fully coupled, implicit, direct solution technique for fluid and heat flow (Pruess and Schroeder, 1980). The accuracy of the MINC-method has been verified by comparison with analytical solutions for a number of limiting cases (Pruess and Narasimhan, 1982; Lai, Bodvarsson, and Pruess, 1982). In the next section we shall present results for production-injection in a five-spot well pattern in a two-phase fractured reservoir. Subsequently, results for a two-well system representative of a Japanese geothermal field will be briefly described.

FIVE-SPOT IN A TWO-PHASE FRACTURED RESERVOIR

The reservoir parameters as given in Table 2 correspond to the case of a low permeability reservoir similar to the Baca geothermal field in New Mexico. The basic mesh (1/8 of a five-spot) is shown in Figure 9. Each grid block of this "primary" mesh is partitioned into a number of interacting continua using the method of Pruess and Narasimhan (1982), assuming three sets of plane, perpendicular, infinite fractures.

CONSTANT RATE

In the first set of calculations, the production rate was fixed at 30 kg/s, which corresponds to the more productive wells in the Baca reservoir.

Our results show that without injection, pressures will decline rapidly in all cases. The times after which production-well pressure declines below 0.5 MPa are: 1.49 yrs for a porous medium, 2.70 yrs for a fractured reservoir with D = 150 m, $k_m = 9x10^{-17}$ m^2, and 0.44 yrs for D = 50 m, $k_m = 1x10^{-17}$ m^2. Note that the fractured reservoir with large k_m ($9x10^{-17}$ m^2) has a greater longevity than a porous reservoir. The reason for this is that the large matrix permeability provides good fluid supply to the fractures, while conductive heat supply is limited. Therefore, vapor saturation in the fractures remains relatively low, giving good mobility and a more rapid expansion of the drained volume.

The results obtained with 100% injection demonstrate the great importance of injection for pressure maintenance in fractured reservoirs with low permeability. Simulation of 90 years for the porous medium case, and 42 and 103 years, respectively, for fractured reservoirs with D = 50 m and D = 250 m ($k_m = 10^{-17}$ m^2), showed no catastrophic thermal depletion or pressure decline in either case. These times are significantly in excess of the 30.5 years needed to inject one pore volume of fluid. Figure 10 shows temperature and pressure profiles along the line connecting production and injection wells for the three cases studied after 36.5 years of simulated time. The temperature of the porous-medium case and the fractured reservoir with D = 50 m agree remarkably well, indicating an excellent thermal sweep for the latter (see also Bodvarsson and Tsang, 1982). The temperature differences $\Delta T = T_m - T_f$ between matrix and fractures are very small: after 36.5 years, we have $\Delta T \approx .2°C$ near the production well, .001°C near the injection well, and less than 5°C in between. In the D = 50m case, produced enthalpy remains essentially constant at h = 1.345 MJ/kg. It is interesting to note that this value is equal to the enthalpy of single-phase water at original reservoir temperature T = 300°C. Thus, there is an approximately quasi-steady heat flow between the hydrodynamic front at T ≈ 300°C and the production well, with most of the produced heat being supplied by the thermally depleting zone around the injector.

At the larger fracture spacing of D = 250 m, the contact area between matrix and fractures is reduced, and portions of the matrix are at larger distance from the fractures. This slows thermal and hydrologic communication between matrix and fractures, causing the reservoir to respond quite differently to injection. More of the injected water remains in the fracture system, so that produced enthalpy and boiling rates are reduced. After 36.5 years, thermal sweep is much less complete, with temperature differences between matrix and fractures amounting to 16°C, 118°C, and 60°C, respectively, near producer, near injector, and in between. Temperatures increase monotonically away from the injection well at D = 250 m, whereas for D = 50 m there is a region of lower temperature around the production well caused by heat loss in boiling. Two-phase conditions with intense boiling occur within 200 m of the producer after 36.5 years for D = 50 m fracture spacing. In contrast, the fracture system becomes completely water filled after 30 years in the case with D = 250 m. For the particular production and injection rates employed in this study, thermal depletion is slow enough that even at a large fracture

spacing of D = 250 m, most of the heat reserves in the matrix can be produced. We are presently investigating energy recovery in the presence of a prominent short-circuiting fault or fracture between production and injection wells, under which conditions less favorable thermal sweeps are expected.

WELL ON DELIVERABILITY

The second set of calculations specifies production in a more realistic way with a productivity index and a constant downhole pressure of p = 2 MPa. Production rates decline with time as the reservoir is being depleted. Injection was specified as a fraction of the (time-dependent) production rate. The parameters used in the simulations are given in Table 3.

In the study we consider 3 cases: no injection, injection of 50% of the produced fluids, and 100% injection (injection rate equals the production rate). The production rate versus time for the three cases is shown in Figure 11. In the no-injection case the flow rate declines rapidly due to the low permeability of the fracture system. The calculated flow rate and its decline compares well to the observed data from well Baca-13 (Hartz, 1976). The calculated flow rates for the 50% injection case decline also quite rapidly, but the rate is considerably higher at all times due to the pressure support from the injection. After an initial decline the flowrate for the 100% injection case is fairly stable at 60 kg/s. The high injection rate gives steady-state flow in the reservoir, thereby keeping the production well pressure constant. The enthalpy transients for the three cases are shown in Figure 12. Boiling around the production well causes the enthalpy to increase steadily in the no injection case. In the cases with injection the enthalpy is lower at all times, and actually decreases gradually in the case of 100% injection. The gradual decrease in enthalpy causes the slight increase in flow rates with time due to relative permeability effects.

The net energy output for the three cases is shown in Figure 13. The net energy output is here defined as the product of the flow rate and the flowing enthalpy at any given time. It is seen that injection can greatly enhance the energy output, with energy recovery increasing with the injection factor. Thus, the increase in production rate made possible by pressure support from injection is larger than the loss in produced enthalpy.

In the case of 100% injection energy output is stable while practically all of the energy contained in the rock is swept by the injected waters. The simulation results show that for the parameters chosen there is no danger of premature thermal breakthrough, as a rather uniform thermal sweep from the reservoir rocks is attained (cf. Bodvarsson and Tsang, 1982).

DOUBLET PROBLEM

As reported by Horne (1982) thermal interference between injection and production wells has been observed at several fields in Japan. As a result of injection the enthalpy of the production wells has declined with time. The data given by Horne (1982) show that in many cases the injection wells are located very close to the production wells (100-200 meters), which, together with relatively large fracture spacings, may explain that thermal interference is noted within a few years after starting injection. We have performed simulation studies using data from Japanese fields to study the time of thermal breakthrough and the production temperature decline with time. These studies are intended to show that the experience in Japan can be explained using our current understanding of cold water injection into fractured reservoirs. We consider a doublet system in a fractured reservoir, using the numerical simulator PT (for pressure and temperature, Bodvarsson, 1981). Values for the parameters used are identical to those shown in Table 1; in addition we assume a reservoir temperature of 250°C, an injection temperature of 100°C, a well spacing of 150 m and a fracture spacing of 50 m. The temperature of the produced water is shown as a function of time in Figure 14. The figure shows that within 1.5-2 years after injection started production temperature declines significantly. This result compares closely with observed behavior at the Kakkonda geothermal field in Japan.

SUMMARY

We have presented several recent studies carried out at Lawrence Berkeley Laboratory on injection of cold fluids into fractured geothermal reservoirs. Analytic methods have been used to study the movement of the thermal fronts in reservoirs (a) with a series of horizontal fractures; and (b) with an equally spaced vertical and horizontal fracture network (naturally fractured reservoir case). The results from these studies show that excellent thermal sweep can be achieved in fractured reservoirs if injection wells are appropriately located. Simple formulas are presented which should be useful for siting injection wells in such a way that premature thermal breakthrough is avoided.

A numerical method was presented which permits the modeling of heat and multiphase fluid flow between rock matrix and fractures in a detailed and fully transient way. Application to doublet and five-spot production-injection systems demonstrates that fluid injection is a very effective means for maintaining pressures in fractured reservoirs with low permeability. The numerical results are consistent with analytic results, indicating that excellent thermal sweeps are possible even for large fracture spacings of several hundred meters.

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FIGURE CAPTIONS

Fig. 1. Basic model of an injection well penetrating a reservoir with equally spaced horizontal fractures.

Fig. 2. Schematic of analytical model.

Fig. 3. Plots of thermal fronts at various times τ for $\theta < 0.01$; is dimensionless vertical distance and ξ is dimensionless advancement along the fractures.

Fig. 4. Plots of thermal fronts at various dimensionless times τ for $\theta >$ 100.

Fig. 5. Type curves for the movement of the thermal front in the fracture for various values of θ.

Fig. 6. Idealized model of a fractured porous media.

Fig. 7. 1-dimensional approximation of heat conduction in rock matrix blocks.

Fig. 8. Basic computational mesh for fractured porous media, shown here for simplicity for a two-dimensional case. The fractures enclose matrix blocks of low permeability, which are subdivided into a sequence of nested volume elements.

Fig. 9. Mesh for five-spot well pattern.

Fig. 10. Temperature and pressure profiles for five-spot.

Fig. 11. Production rate versus time for the five-spot cases.

Fig. 12. Enthalpy transients for the five-spot cases.

Fig. 13. Total energy output versus time for the five-spot cases.

Fig. 14. Production temperature versus time for the doublet case.

Table 1: Parameters Used in Example

Injection rate ,q	:	20 kg/s
Fluid density, ρ_w	:	1000 kg/m^3
Fluid heat capacity, c_w	:	4200 J/kg.°C
Thermal conductivity, λ	:	2.0 J /m.s.°C
Reservoir thickness, H	:	500 m
Rock density, ρ_r	:	2700 kg/m^3
Rock heat capacity, c_r	:	1000 J/kg.°C

Table 2: Parameters Used in Numerical Simulations

	Five-Spot
Formation	
rock grain density	2600 kg/m^3
rock specific heat	950 J/kg °C
rock heat conductivity	2.22 W/m °C
porosity	.10
permeability x thickness	1.83×10^{-12} m^3
reservoir thickness	305 m
matrix permeability	10^{-15} m^2, 9×10^{-17} m^2, 10^{-17} m^2
Fractures	
three orthogonal sets	
aperture	(a)
spacing	5 m, 50 m, 150 m
permeability per fracture	(a)
equivalent continuum permeability	6×10^{-15} m^2
equivalent continuum porosity	.10
Relative Permeability	
Corey-curves	$S_{\ell r} = .30$, $S_{gr} = .05$
Initial Conditions	
temperature	300°C
liquid saturation	99%
Production	
production rate	30 kg/s
Injection	
rate	30 kg/s
enthalpy	5×10^5 J/kg

(a) fractures modeled as extended regions of high permeability, with a width of ~ .2 m

Table 3: Parameters Used in Well Productivity Calculations

Initial temperature	:	300°C
Initial vapor saturation	:	0.01
Injection temperature	:	150°C
Matrix permeability	:	1×10^{-18} m^2
Well spacing	:	1000 m
Fracture spacing	:	250 m
Bottomhole pressures	:	20 bars
Productivity index	:	1.0×10^{-14} m^3

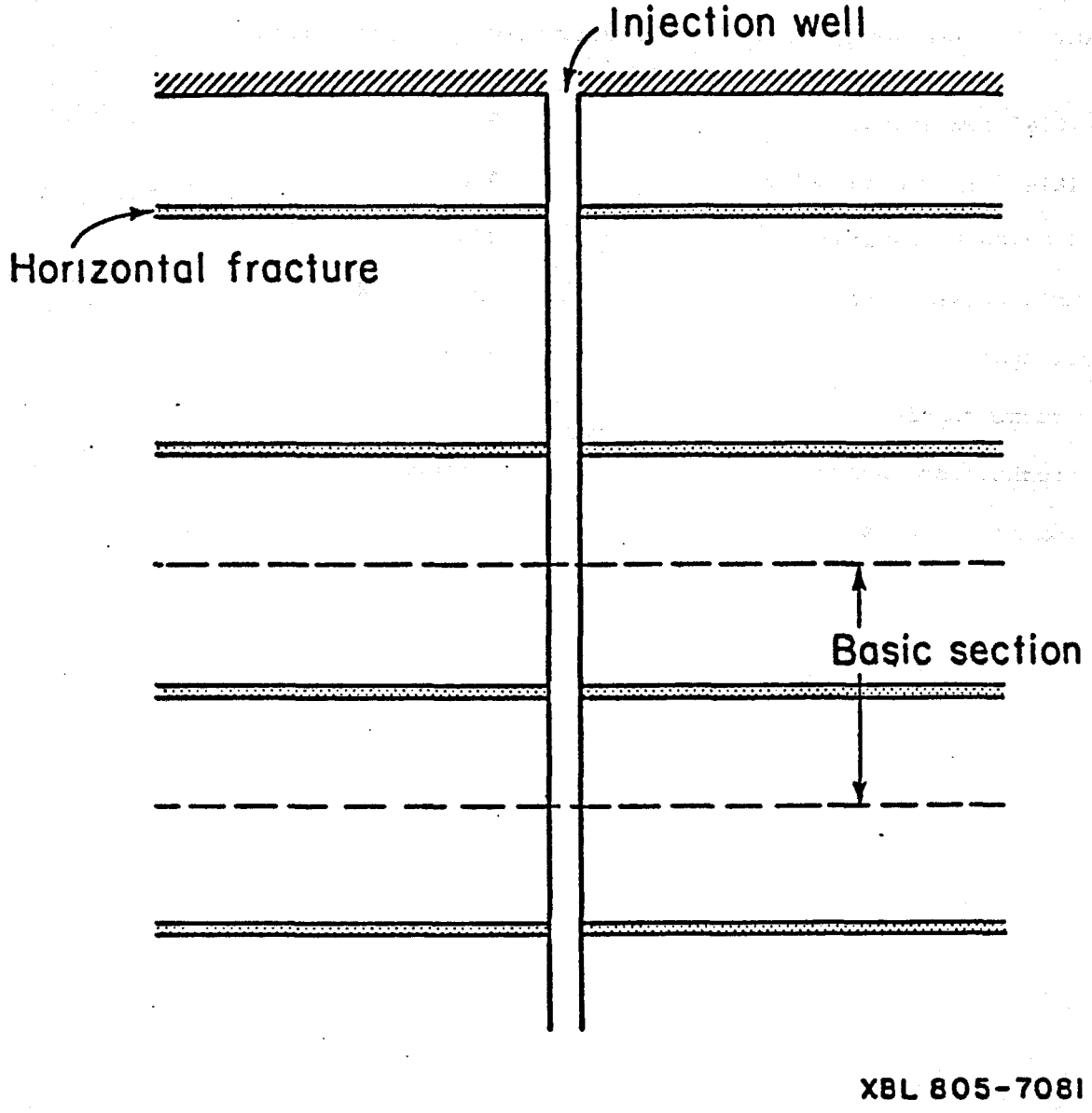


Fig. 1. Basic model of an injection well penetrating a reservoir with equally spaced horizontal fractures.

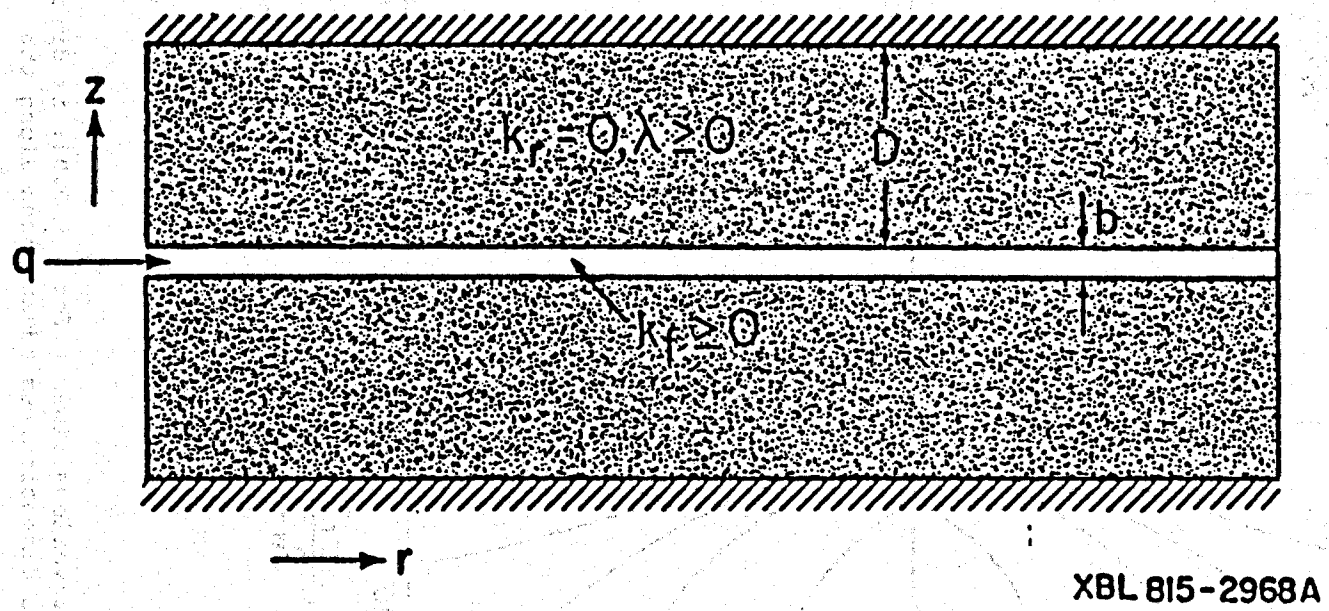


Fig. 2. Schematic of analytical model.

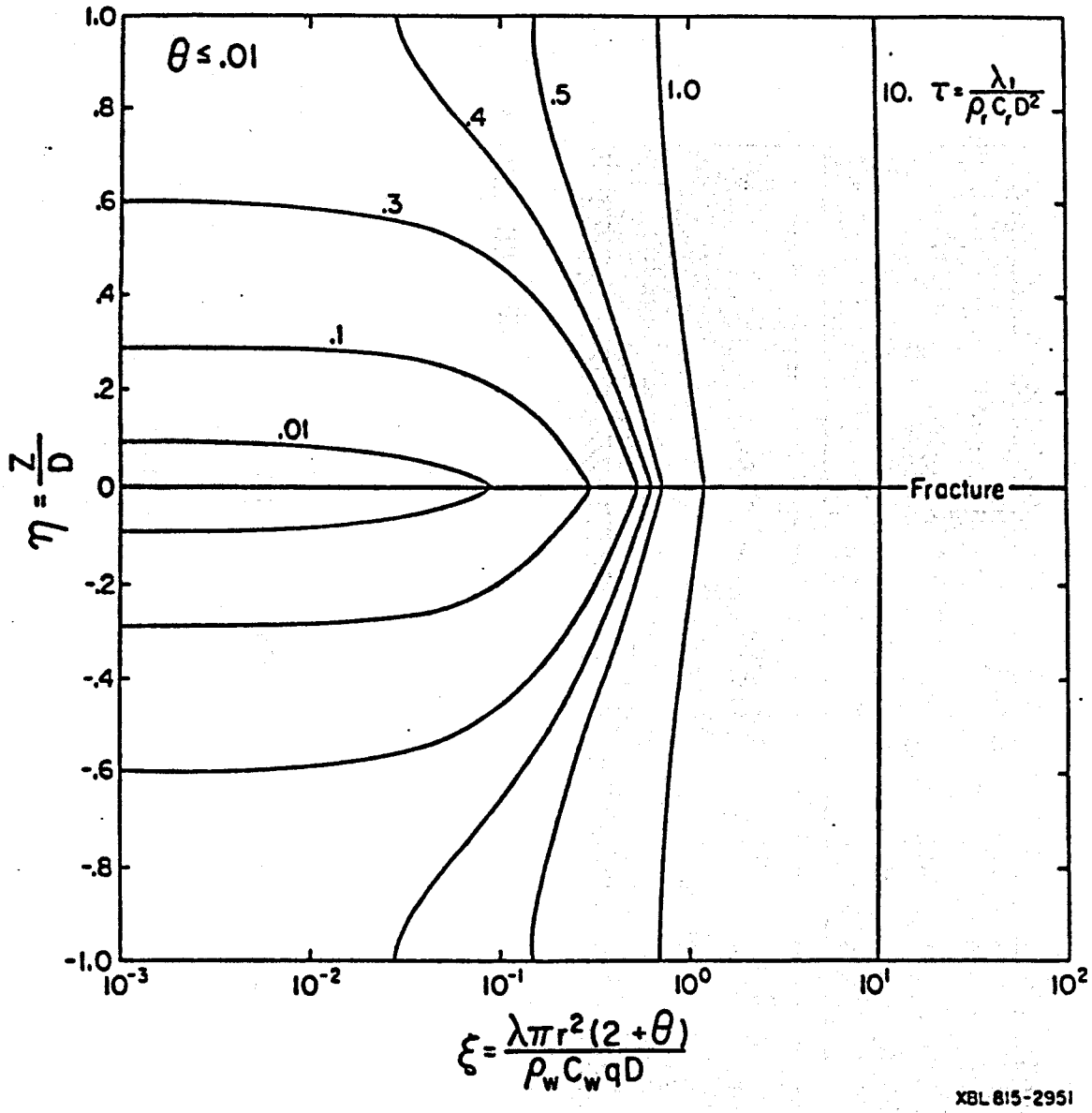


Fig. 3. Plots of thermal fronts at various times τ for $\theta < 0.01$; is dimensionless vertical distance and ξ is dimensionless advancement along the fractures.

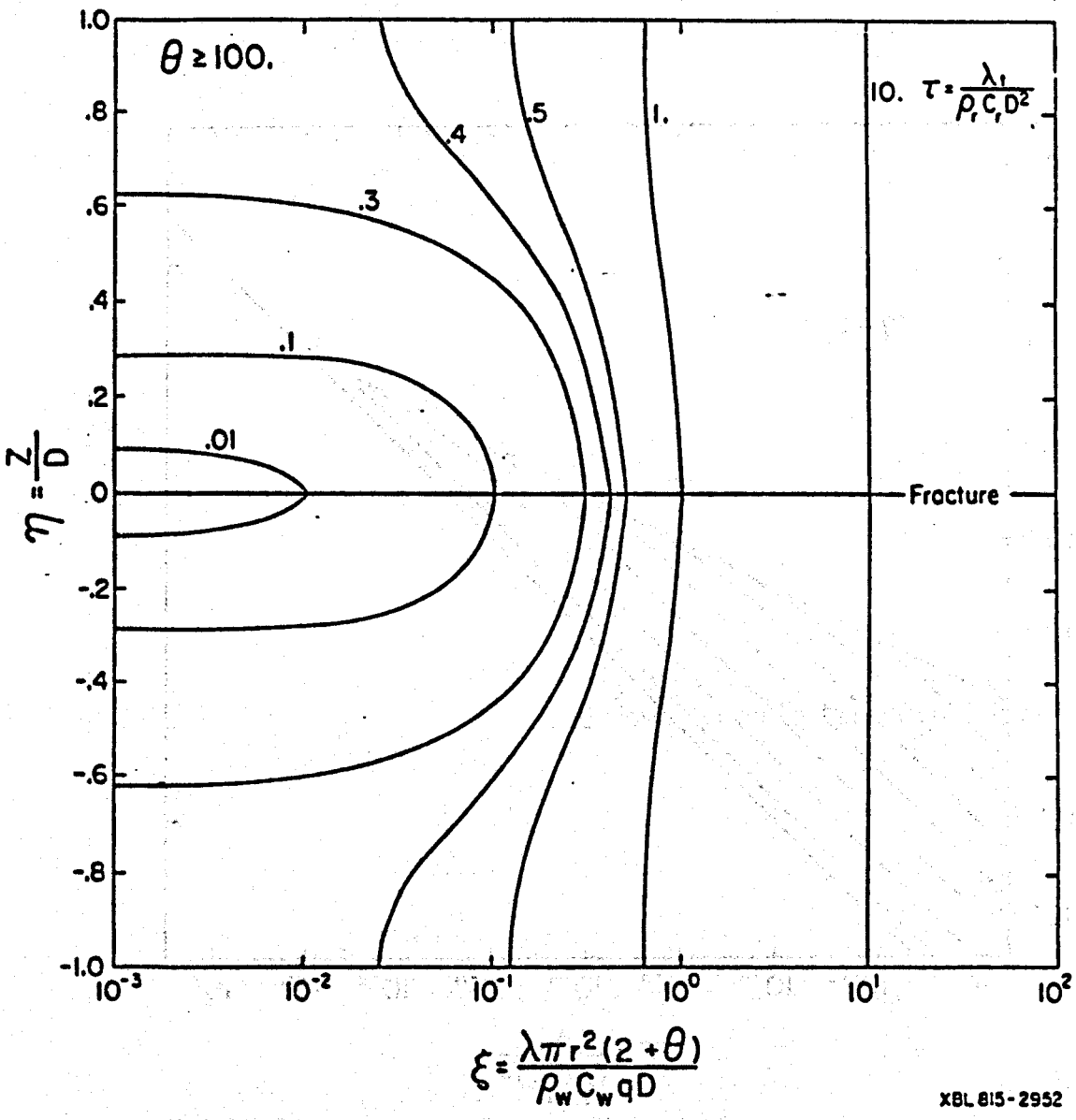
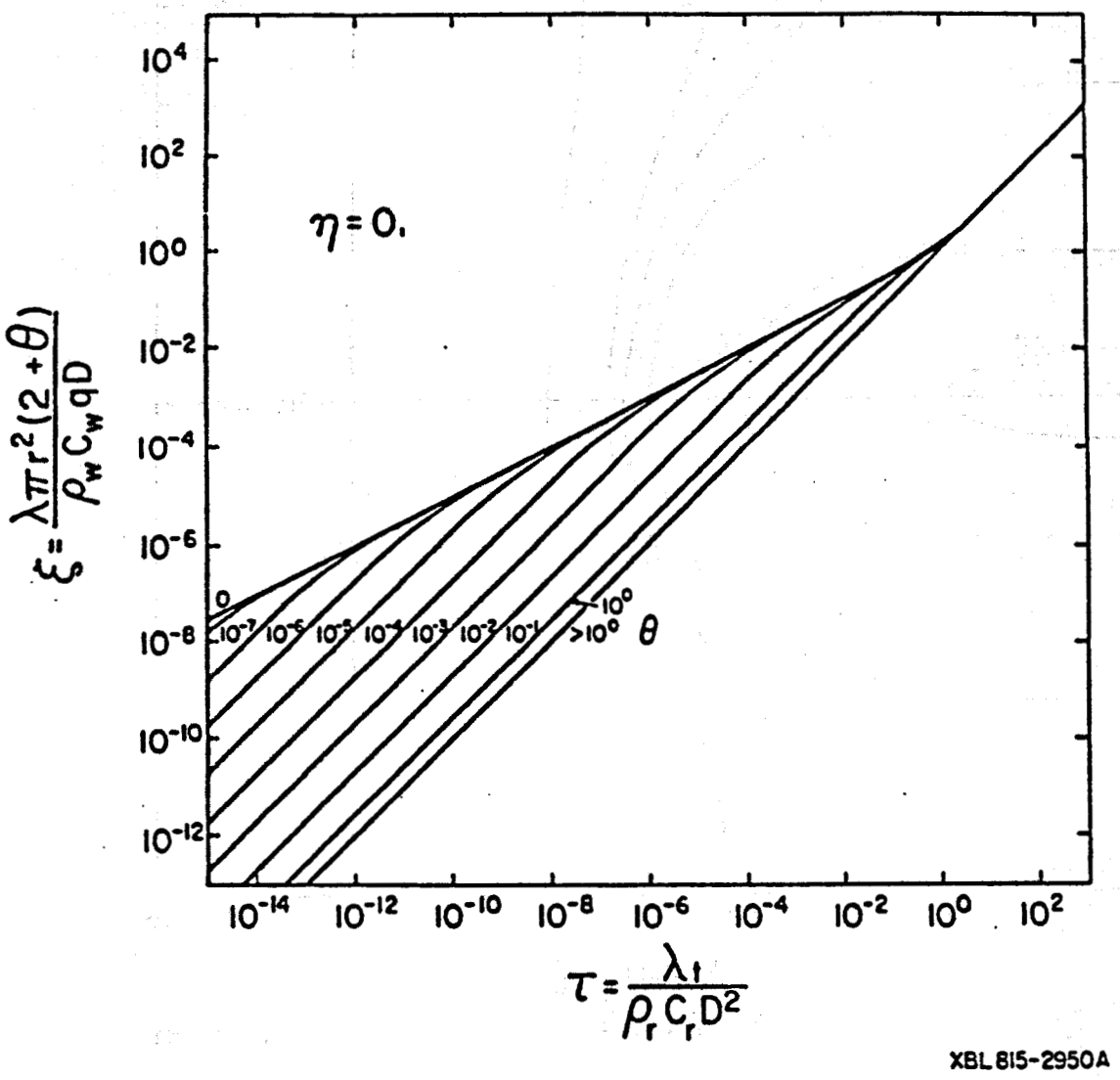


Fig. 4. Plots of thermal fronts at various dimensionless times τ for $\theta >$ 100.



XBL 815-2950A

Fig. 5. Type curves for the movement of the thermal front in the fracture for various values of θ.

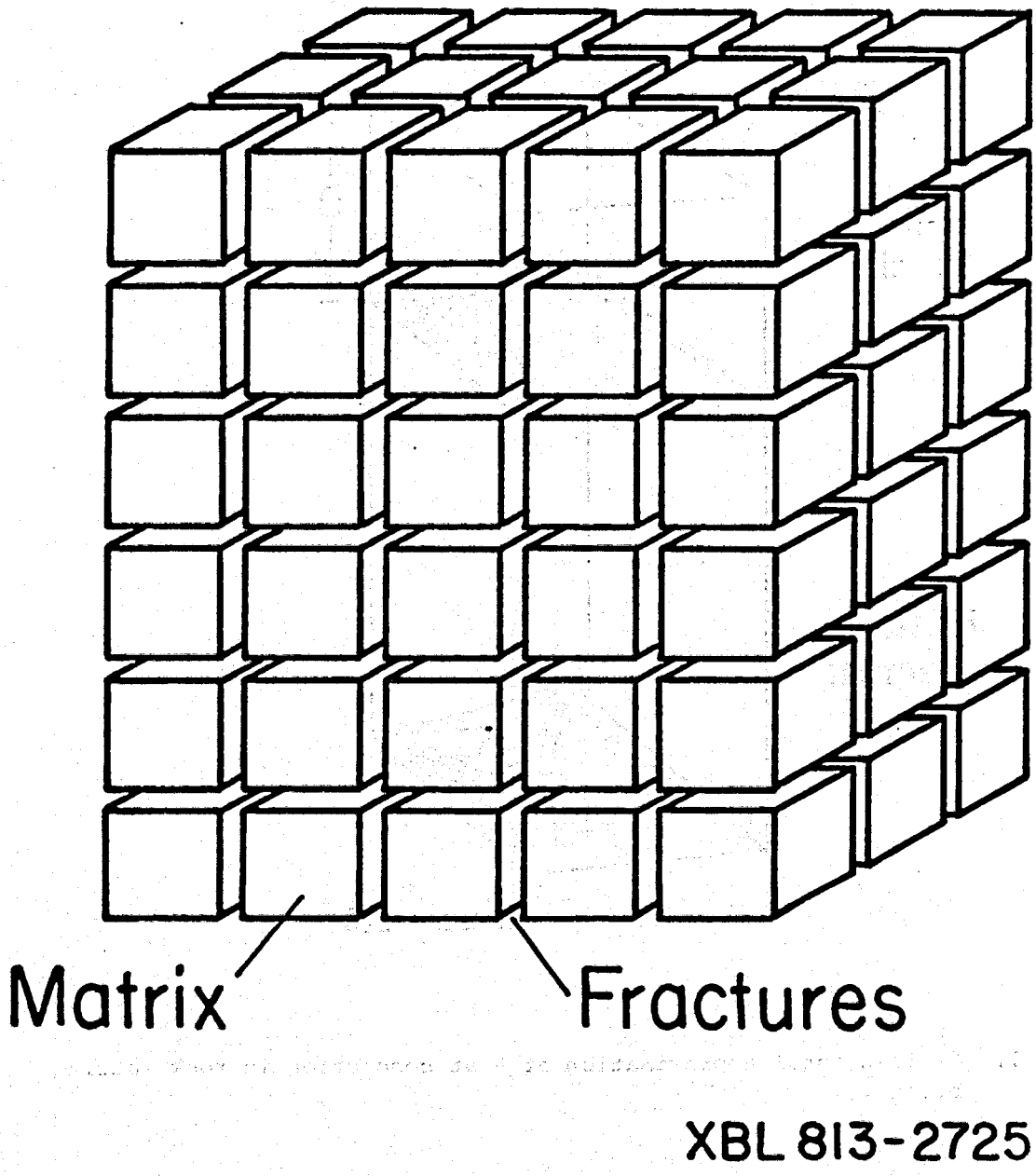


Fig. 6. Idealized model of a fractured porous media.

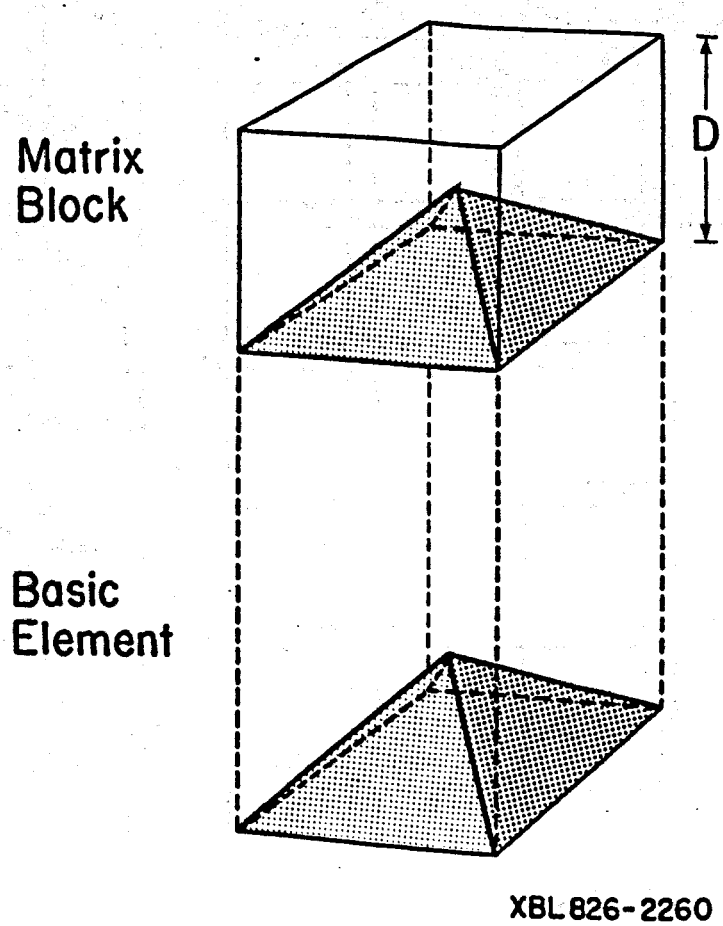
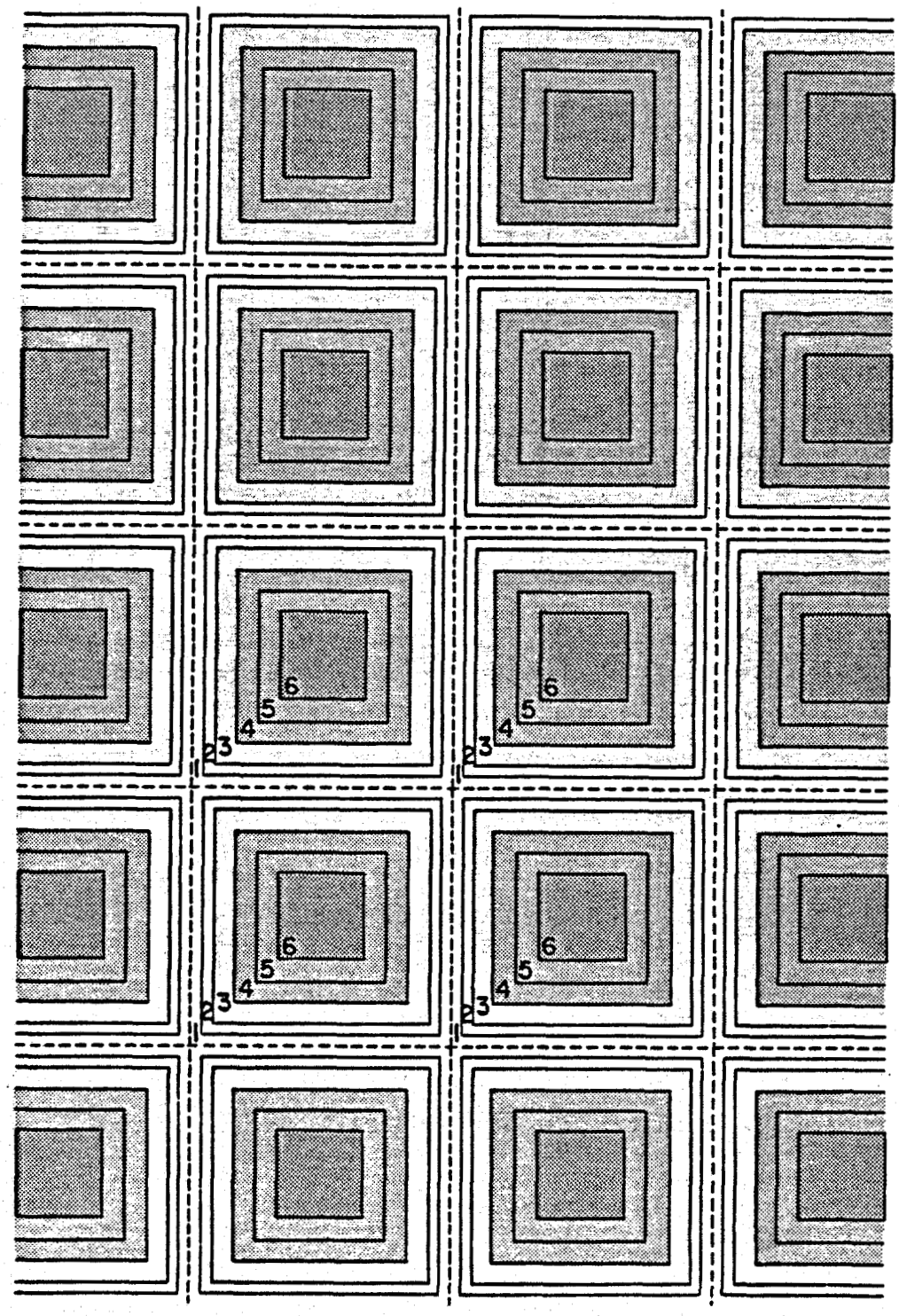


Fig. 7. 1-dimensional approximation of heat conduction in rock matrix blocks.



XBL 813-2753

Fig. 8. Basic computational mesh for fractured porous media, shown here for simplicity for a two-dimensional case. The fractures enclose matrix blocks of low permeability, which are subdivided into a sequence of nested volume elements.

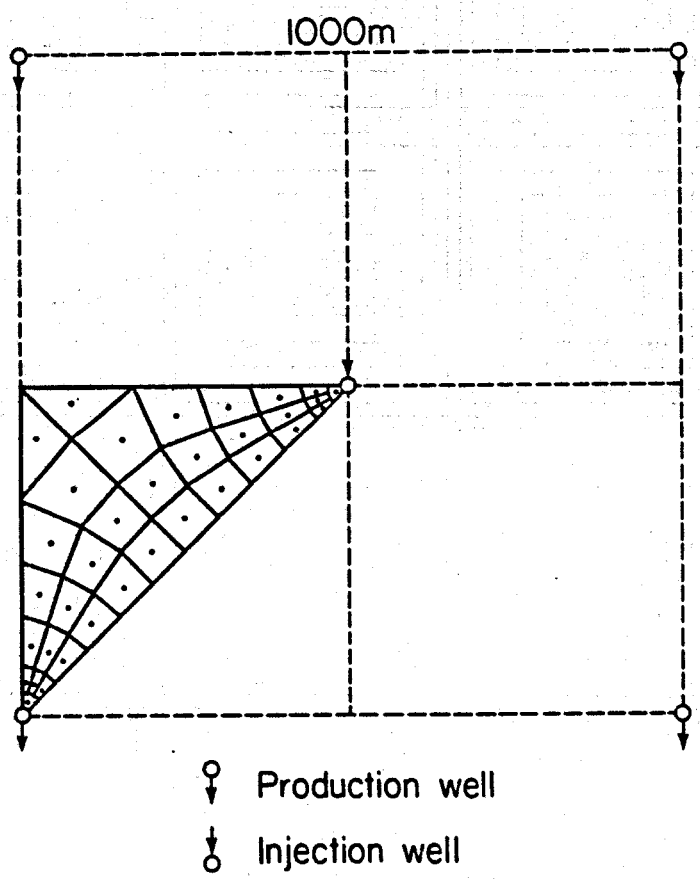


Fig. 9. Mesh for five-spot well pattern.

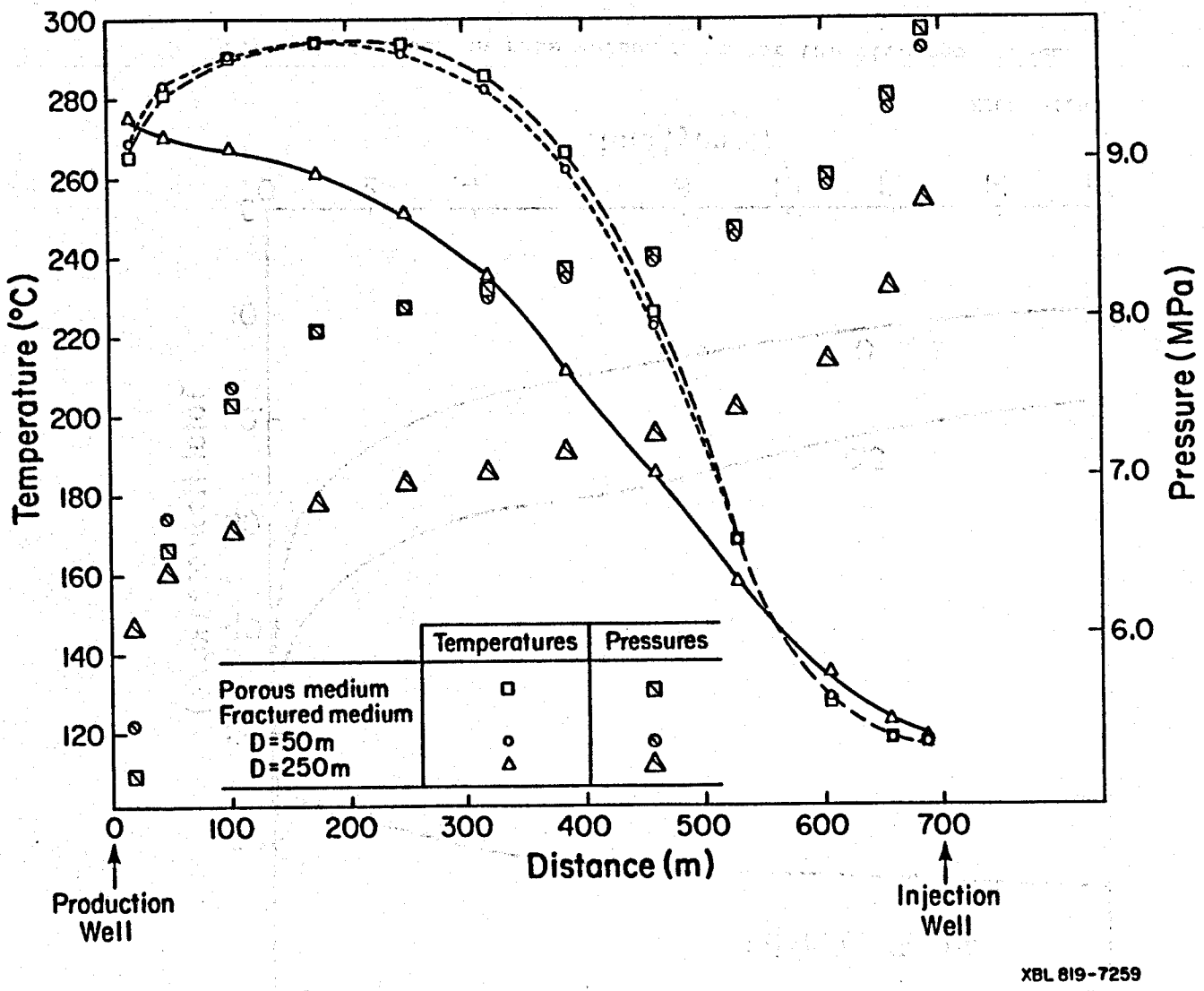


Fig. 10. Temperature and pressure profiles for five-spot.

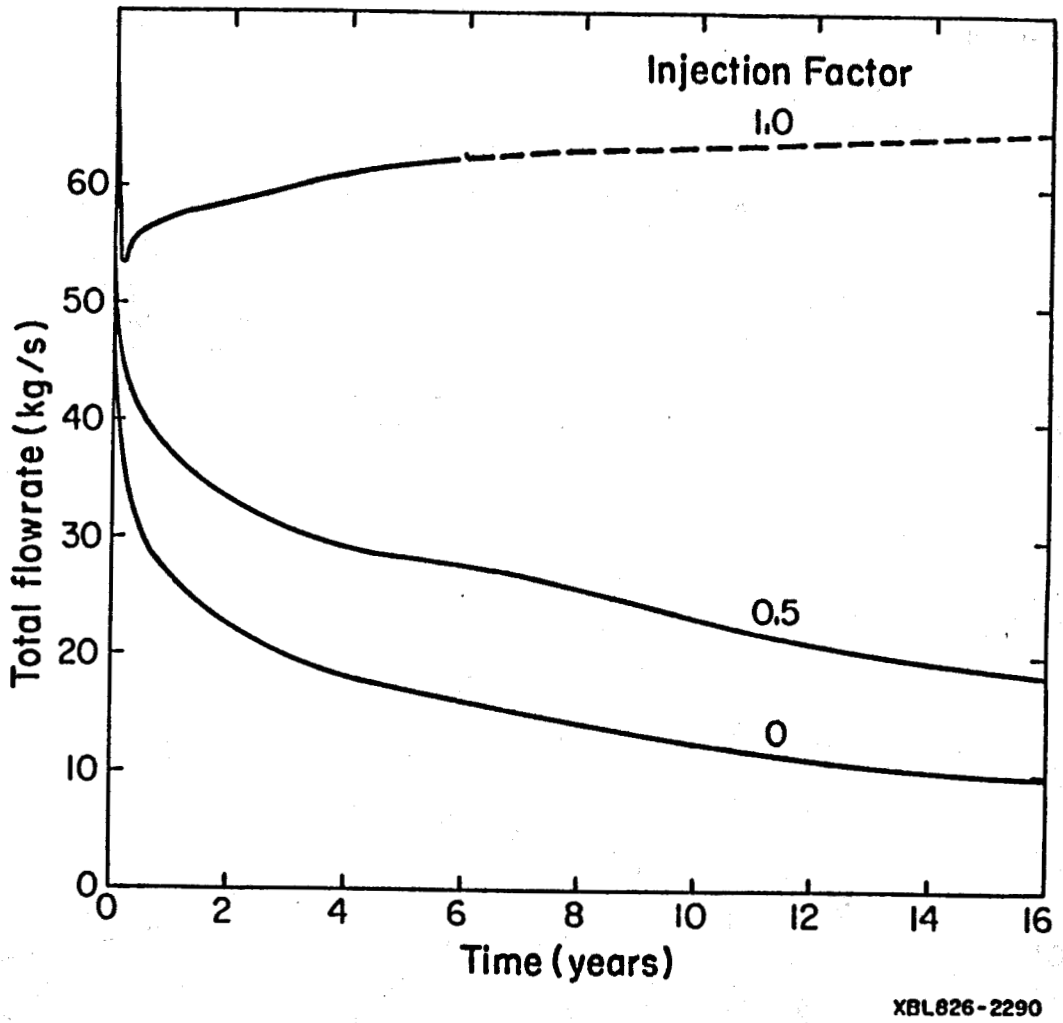


Fig. 11. Production rate versus time for the five-spot cases.

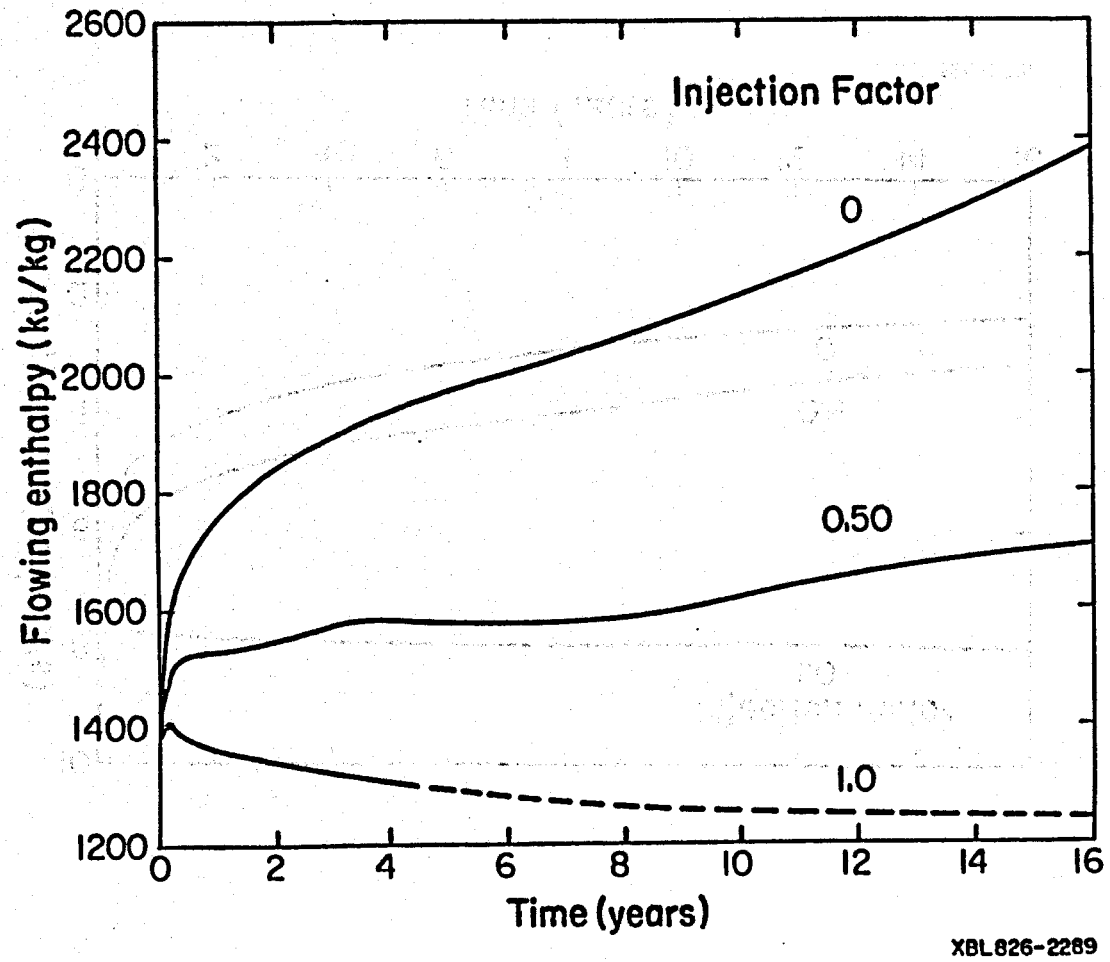


Fig. 12. Enthalpy transients for the five-spot cases.

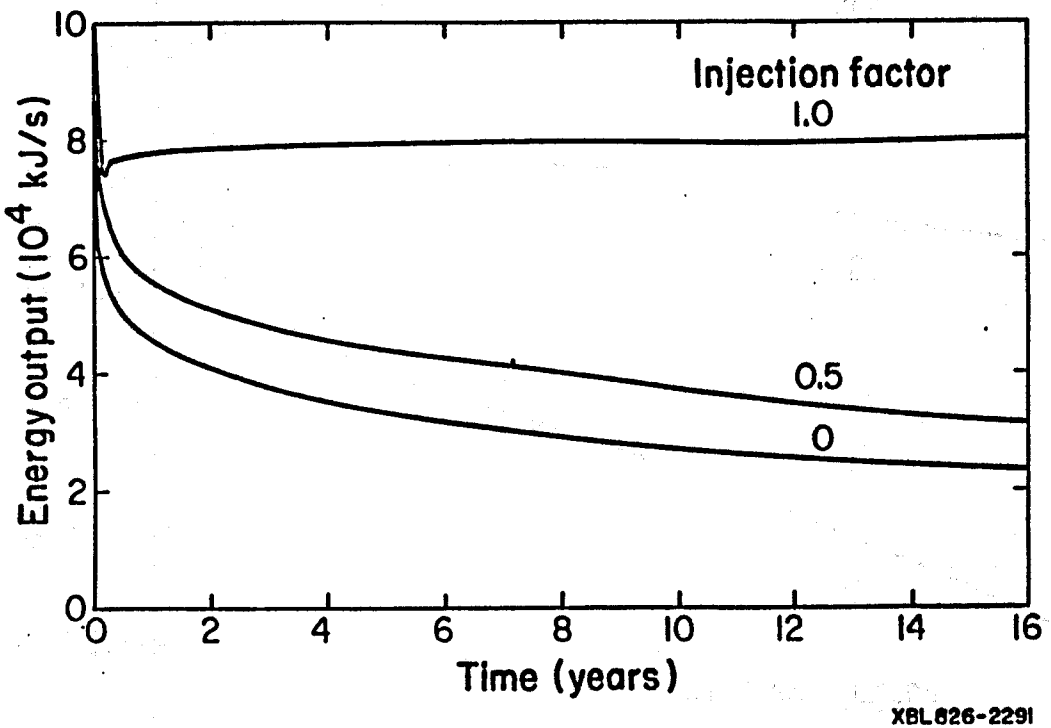


Fig. 13. Total energy output versus time for the five-spot cases.

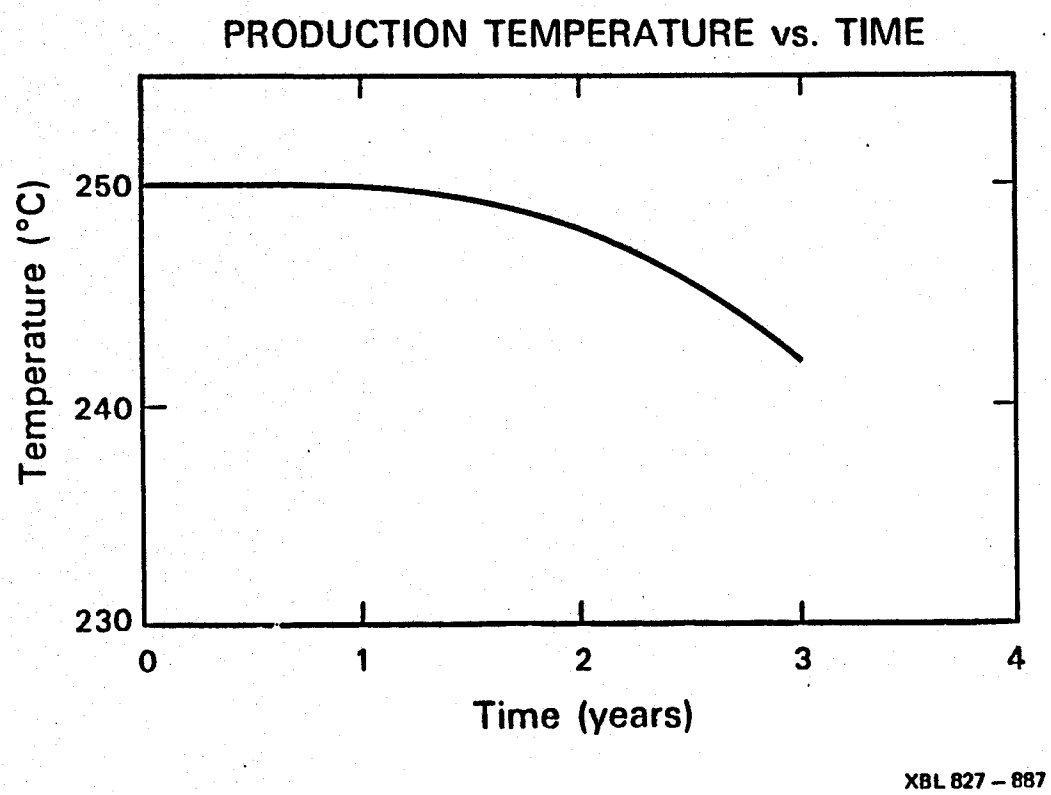


Fig. 14. Production temperature versus time for the doublet case.

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