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DOUBLET HEAT SWEEP MODEL WITH BOUNDED INITIAL TEMPERATURE DISTRIBUTION

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ABSTRACT

The SGP 1-D Heat Sweep Model has been improved to simulate production fluid cooldown under partial reinjection recharge through a fractured hydrothermal reservoir with a given temperature distribution. The model was developed as a 1-D doublet flow model with the assumption of equal and linear flow through a series of N crescents each carrying 1/N of the reinjection recharge flowrate. For a uniform initial reservoir temperature infinite in geometry for doublet flow, the heat content available above a useful abandonment temperature increases rapidly with increasing crescent number. The result is a very long cooldown time to the abandonment temperature. The improved model limits the volume of the reservoir at mean initial temperature to a defined geometry. In the absence of field data on temperature distribution around an isolated injection-production well pair, several possibilities are explored; for example, uniform temperature in a cylinder of radius equal to one half of the distance between the well pair, with temperature distribution decreasing as 1/N thereafter. Other distributions examined are a step function, a normal distribution, and an exponential decline from the line normal to the well pair. The simulated cooldowns resulting from these temperature distributions are compared to the prior results reported for uniform temperature distribution at two Mexican geothermal fields. The first is the La Primavera well pair scheduled for the first power unit. The simulations were based on preliminary data on the actual temperature distribution at the flow horizon. The second is the isolated well pair in the El Chino zone of the Los Azufres geothermal field, where little temperature data are available. The results show considerable decline in cooldown time to the abandonment temperature. When measured temperature distributions are made, the model can be changed to reflect doublet flow more accurately. This will require a more complicated heat sweep model.

INTRODUCTION

The Stanford Geothermal Program 1-D Heat Sweep Model was developed as a means of estimating energy extraction by reinjection recharge in fractured-rock geothermal resources in a simple way when reservoir and production data are sparse. The model is especially useful in new and undeveloped fields where only limited geologic, thermodynamic, and production data are available and where recharge experience in non-productive wells does not exist. The model calculates production fluid temperature based on estimated condition of reservoir structure, return flow geometry, and mean thermal properties of the reservoir formation for given steady production conditions. A description of the original 1-D linear heat sweep model was given by Hunsbedt, Lam, and Kruger (1984) and several applications are listed in Kruger (1988).

The linear model was improved by Lam (1986) to provide ability to examine more complex flow geometries and mixing of reinjected recharge fluid with resource fluid while maintaining the simple 1-D nature of the simulations. The linear heat sweep model now allows for radial return flow of reinjected fluid and for fluid mixing at the production zone of sweep fluid at its heat-extracted temperature with resource fluid cooling at a constant rate. More recently, doublet flow was added as another flow geometry in which the intrinsic 2-D nature of doublet flow is approximated as 1-D flow by linear flows in a series of flow crescents extending normal to the line through the doublet pair of injection-production wells. The hydrologic flow between wells in a uniform flow field was described by Grove, Beetem, and Sower (1970). The 1-D doublet heat sweep model calculates the heat extraction as linear heat sweeps in the series of flow crescents. A description of the model is given in Lam and Kruger (1987).

One of the simplifications made in the heat sweep model is an assumption of a uniform-temperature formation of hot, fractured rock blocks encompassing the reinjection return flow geometry between the injection and production wells. The extractable heat content of this mass of rock above the recharge temperature is given by

$$H = [\phi \rho wVwCw + (1-\phi) \rho rVrCr] * (To - Tr) \qquad (1)$$

where ϕ = formation porosity
ρ = mean phase density
V = swept formation volume
C = phase specific heat
To = mean initial formation temperature
Tr = recharge fluid temperature
and w,r refer to water and rock phases, respectively.

The assumption of a uniformly-distributed thermal energy reservoir is adequate for the linear and radial return flow geometries in that the uncertainty in the flow boundaries is probably not much greater than the unknown non-uniformity in the reservoir structural and thermal characteristics. On the other hand, this assumption for the intrinsic 2-D doublet flow model with its series of expanding crescent flow volumes is not adequate for two reasons: (1) the use of a uniform high initial temperature for the outer crescents involves a reservoir volume much greater than the resource volume resulting in an unrealistic extractable heat content; and (2) the streamline flow away from the direct path to the production well makes a negligible contribution to the cooldown to abandonment temperature but provides a long period of production fluid at the mean initial reservoir temperature. The result of these two phenomena results in an overestimation of the cooldown time to the abandonment temperature.

To evaluate the effect of temperature distribution on the extraction of heat from large rock blocks and still maintain the 1-D nature of the doublet flow model, an exercise was carried out to observe the effect of varying the initial temperature distribution in the flow geometry on the cooldown behavior of the produced fluid. The distributions were arbitrarily set normal to the axis of the injection-production well pair with a uniform temperature in each crescent. Figure 1 shows the series of assumed initial temperature distributions: (1) a circular reservoir of radius one-half the well separation distance containing half of the injection return flowrate with temperature further away declining with crescent number, N, as 1/N; (2) a step function, with crescent number distance taken from the temperature-depth profiles estimated by Maciel (1988) for the well pair PR2-PR1 at the La Primavera geothermal field; (3) a normal distribution to the same external temperature distance as the step function; and (4) an exponential temperature decline from the well pair

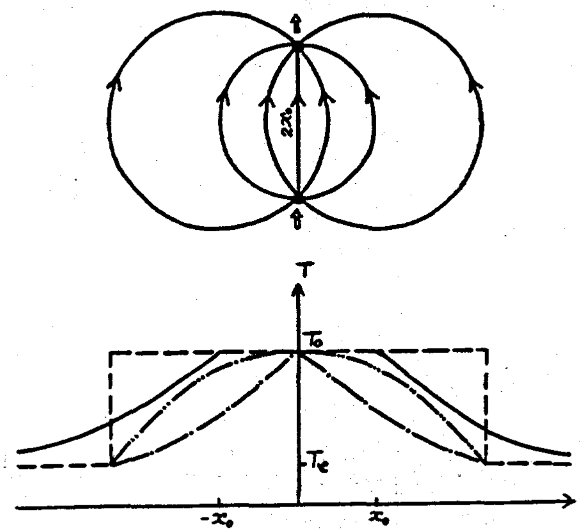

Figure 1. Temperature distributions for doublet flow simulations: (a) doublet flow as a series of crescents bounded by streamlines; (b) circular, step, normal, and exponential temperature distributions.

axis to the same external temperature distance. The same fractional distances were used for the El Chino well pair Az3-Az9 in the Los Azufres geothermal field.

1-D DOUBLET HEAT SWEEP MODEL WITH TEMPERATURE DISTRIBUTION

The 1-D Heat Sweep Model describes thermal energy extraction from a distribution of fractured rock blocks in a linear reservoir of uniform width and depth (Hunsbedt, et al, 1984). Energy extraction is based on the heat transfer from an irregular-shaped rock block investigated by Kuo et al (1977) and extended by Iregui, et al (1978) to an ensemble of rock blocks by size distribution. The ensemble is modeled as lumped equivalent-volume spheres with thermal time constant, τ, given by Hunsbedt, et al (1978) as

$$\tau = R^2/3\alpha \, (0.2 + 1/Bi) \qquad (2)$$

where R = equivalent radius of the rock blocks
α = rock thermal diffusivity
Bi = rock Biot number (= hR/k)
h = reservoir heat transfer coefficient
k = rock thermal conductivity

The rate of heat extraction is determined by both the thermal time constant for the rock block distribution and the mean residence time of the recharge fluid from the reinjection well to the production well. The 1-D model is formulated in heat transfer equations for both the fluid and rock phases, in terms of the rock thermal time constant and fluid residence time. The equations are transformed into Laplace space and solved analytically. The resulting rock and fluid temperatures are converted into real space temperatures with the numerical algorithm reported by Stehfest (1970).

The linear and radial flow models have been useful in simulations involving numbers of injection or production wells or where structural features can act as boundaries to reinjection return flow. For single injection-production well pairs having no apparent reservoir boundaries, doublet return flow represents the maximum flow time for heat extraction from the reservoir formation as the series of crescent flows result in a spectrum of arrival times. The doublet flow field, sketched in Figure 1a is a series of streamlines emanating from the injection well, extending as circular arcs centered on the normal to the middle of the well pair axis, and converging at the production well. For a uniformly thick reservoir, doublet flow is two-dimensional.

Development of the 1-D doublet heat sweep model was described by Lam and Kruger (1987). The 2-D recharge return flow and associated heat transfer is approximated adequately with the 1-D linear heat sweep model by dividing the total flow field into a large number of flow crescents bounded by streamlines, such that the equivalent mean flow velocity through each narrow crescent characterizes the actual velocity in that crescent. The average flow velocity is uniform and constant in each crescent. The result is an overprediction of heat transfer from the rock blocks to the fluid in the early phase of the transient near the injection well, and underprediction of heat transfer near the midsection. The errors are mainly cancelled over the total sweep flow in each crescent. By integrating the sweep flow and heat transfer of the series of crescents arriving at the production well, the produced fluid temperature is simulated for the given production flowrate.

Generally, the production flowrate exceeds the reinjection flowrate, especially where the separated steam is discharged from the generating-unit turbine. The difference in flow is replaced by mixing the recharge sweep flow with resource fluid near the production well. The resource fluid is considered to originate at a remote location and cool with time at an exponential rate due to entry of colder groundwater or percolation from above. Cooling rates of -0.005/yr have been observed at several geothermal fields.

To estimate the importance of temperature distribution in the doublet flow model as it effects heat transfer in the series of flow crescents, the four different initial temperature distributions away from the well pair axis (shown in Figure 1b) were considered to represent a large spread of heat content available for recharge extraction. The first assumes a circular reservoir boundary with diameter equal to the well pair axis. Within the boundary, the initial temperature is To, decreasing to a given external temperature, Te, outside the boundary as 1/(N-NC/2), where N is the crescent number outside the boundary and NC is the total number of crescents. This temperature distribution should result in the largest extractable heat content above the abandonment temperature, Ta, specified for a given type of generator turbine. It is noted that for doublet flow, half of the crescents, NC/2, are contained within the circular boundary.

The second temperature profile is a step distribution, with a uniform reservoir initial temperature, To, to a given crescent number, and beyond that, a uniform external temperature, Te. The third temperature profile assumes each crescent has a uniform initial temperature which decreases exponentially as a function of distance from the well-pair axis. This distribution should result in the smallest extractable heat content above the abandonment temperature. The initial temperature Ti for crescent i at distance y from the axis is given by

$$Ti = To * \exp[-y/ya * \ln(To/Te)] \quad (3)$$

where ya = maximum distance from well-pair axis at Ta
To = initial temperature at the well-pair axis.

The fourth temperature profile assumes each crescent has a uniform initial temperature which decreases along a normal (bell-shaped) distribution from the well axis. This distribution most-closely follows observed temperature profiles and should account for the most-likely extractable heat content above the abandonment temperature. For this distribution, the initial temperature for crescent i at distance y from the well axis is given by

$$Ti=To*\exp[-((y/ya)*\mathrm{sqrt}(\ln(To/Te)))^2] \quad (4)$$

THE TWO CASE STUDIES

(A) La Primavera Doublet PR2-PR1

The La Primavera geothermal field is located in the State of Jalisco near the city of Guadalajara. The field currently has 8 completed wells, of which 7 are considered for commercial production. Three of these wells, PR1, PR8, and PR9, have been designated for use with the two 5-MW generating units expected in 1989. The non-productive well, PR2, is being considered as a reinjection well for these two units. A study to evaluate the potential for premature thermal breakthrough by the reinjected fluid in this well to the three production wells was reported by Kruger, et al (1988) based on preproduction data compiled by the field operating staff.

For reinjection recharge into well PR2 consisting of brine flow from the separators and condensate from the turbines, the return flow geometry was examined as small-angle radial flow to each well individually, as large-angle radial flow to the three wells collectively, and as doublet flow to the central well. The simulated cooldown curves for the sweep and mixed fluids for this case, based on an infinite initial temperature distribution, are shown in Figure 2a. The key compiled input data for the estimate were initial temperature of 277 C, recharge temperature of 70 C, injection flowrate of 69.8 kg/s, (65% of the production flowrate), with reservoir fluid makeup declining in temperature at a rate of -0.005 /y, and a mean formation porosity of 10 %. The reservoir thickness for return flow was estimated as 410 m over the well separation distance of 1180 m.

(B) El Chino (Los Azufres) Doublet Az3-Az9

The Los Azufres geothermal field is located in the State of Michoacan, about midway between Guadalajara and Mexico City. The field consists of a number of production zones, named after the predominant local faults. The three zones currently with portable 5-MW wellhead generating units are the Tejamaniles zone in the south, the Maritaro zone in the north, and the El Chino zone in the center. The El Chino zone at present has a single production and reinjection well pair, Az9 and Az3, respectively. The zone is located between the El Chino, Laguna, and San Alejo faults which may act as reservoir boundaries for the El Chino reservoir.

A preliminary doublet-flow cooldown analysis for this well pair was reported by Lam and Kruger (1987) for the infinite initial temperature distribution. The simulated cooldown curves for this case are shown in Figure 2b. The heat-sweep time of 5000 years to abandonment temperature was very long compared to the mixed-fluid cooldown time of 500 years (and the no-reinjection cooldown time of 150 years), both based on a constant resource fluid cooldown rate of -0.005 /yr. The key compiled input data for El Chino well pair were initial temperature of 280 C, recharge temperature of 70 C, injection flowrate of 11.3 kg/s (42% of the production flowrate), with the same resource fluid cooldown rate of -0.005 /yr, and a mean porosity of 10 %. The reservoir thickness for return flow was estimated as 240 m over the measured separation distance of 2007 m.

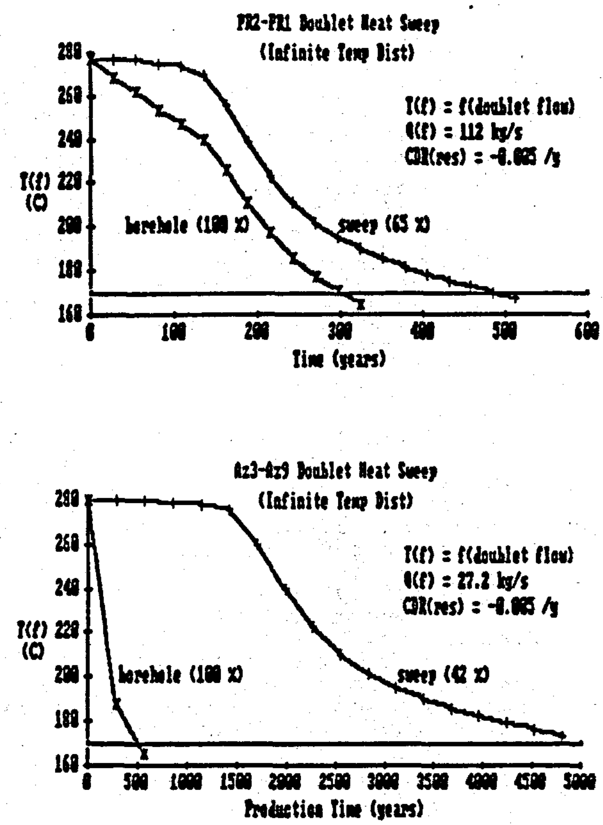

Figure 2. Production fluid cooldown results for the sweep fluid arriving at the production well and the mixed borehole fluid estimated by doublet flow with infinitely uniform initial reservoir temperature for (top) the La Primavera PR2-PR1 well pair and (bottom) the El Chino (Los Azufres) Az3-Az9 well pair.

RESULTS

The 1-D Doublet Heat Sweep Model was adjusted for this study to output the temperature distribution as a function of distance in terms of crescent number. The results, common to the two case studies, are shown in Figure 3. The circular reservoir model (Fig 3a) shows the constant initial temperature to crescent number 25, half of the 50 crescents used for the symmetric half field. This crescent number corresponds to a distance of one well-pair radius, whereas the 50th crescent is at a distance of more than 23 well-pair radii. The other distribution reach the assumed external temperature of 145 C at crescent number 31, corresponding to the abandonment temperature distance on the temperature profiles compiled by the La Primavera staff.

The studies for two well-pair doublet flows under markedly different flow conditions show significant thermal cooldown behavior with reinjection recharge. The La Primavera doublet is relatively closer together (1180 m) than the El Chino doublet (2007 m) with a correspondingly greater reinjection flowrate (68% of 102 kg/s compared to 42% of 27.2 kg/s)at essentially the same initial production temperature.

The results of the simulations for the two well-pair cases are shown as sweep fluid and mixed fluid cooldown curves to the abandonment temperature of 170 C, corresponding to the minimum saturated steam pressure of 8 bar required to operate the 5-MW unit turbines. Figure 4 shows these curves for the La Primavera well pair and Figure 5 for the El Chino well pair. The rapid drop in temperature from the observed initial bottomhole temperature results from the unrealistic colder water production from the crescents outside the thermal reservoir (50 % for the circular reservoir and about 30 % for the other three temperature distributions normal to the actual temperature profiles). The resulting production fluid cooldown times to abandonment temperature for these case studies are listed in Table 1 with the results obtained in the previous studies for the infinitely uniform initial temperature distribution. The calculated heat content of the recharge reservoir above the abandonment temperature and the amount of thermal energy extracted by the sweep fluid for each of the four temperature distributions is given in Table 2.

For the La Primavera doublet, the data show that the cooldown time to abandonment temperature for the circular uniform distribution, comprising half of the number of crescents, is less than half of the time for the infinitely uniform temperature distribution. The cooldown time falls between those for the step and normal distributions. The time for the normal distribution, considered the most realistic one in view of the temperature contours estimated by the La Primavera staff, falls between the step distribution and

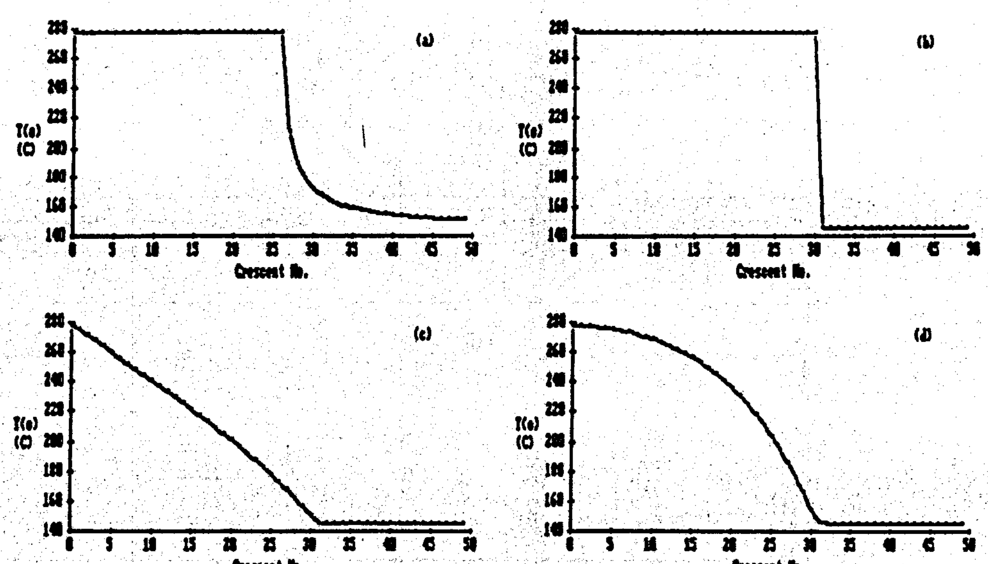

Figure 3. Temperature distribution output from the simulations: (a) circular reservoir with external decreasing temperature to abandonment temperature; (b) step function to given crescent number; (c) exponential decline; (d) normal distribution. For scale, crescent no. 25 is at 1 well-axis radius, crescent 50 is at 23 well-axis radii.

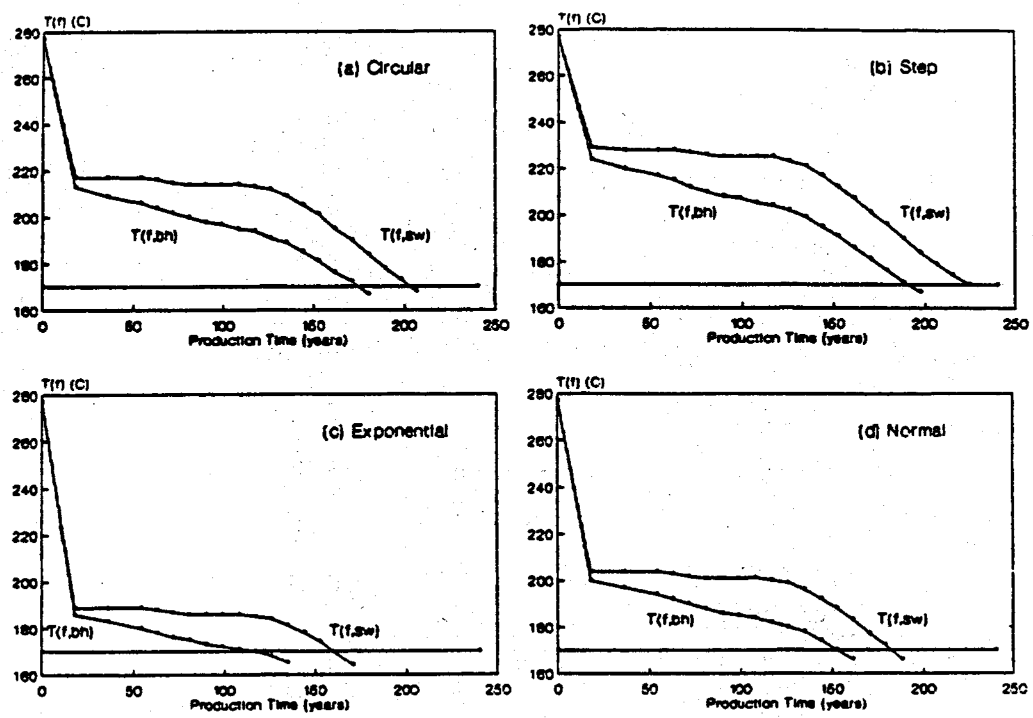

Figure 4. Cooldown results for the La Primavera PR2-PR1 well pair doublet for the given temperature distributions.

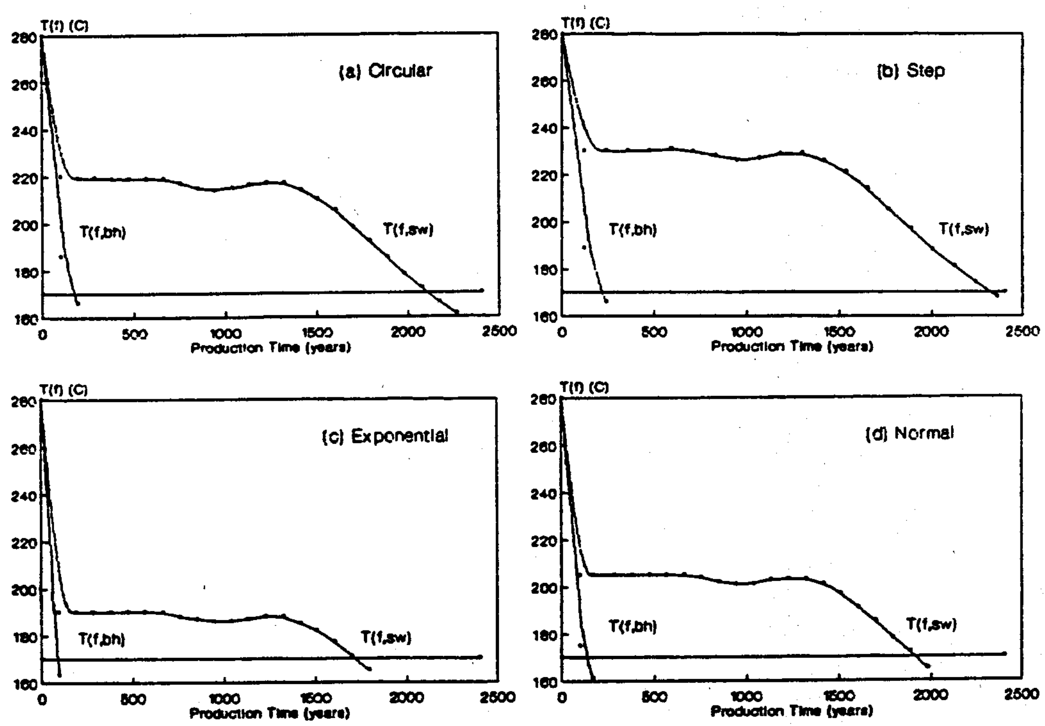

Figure 5. Cooldown results for the El Chino Az3-Az9 well pair doublet for the given temperature distributions.

Table 1
Comparison of Cooldown Times by Temperature Distribution

Assumed Temperature Distribution	Time to Ta = 170 C La Primavera PR2-PR1 Sweep Fluid (y)	Mixed Fluid (y)	El Chino Az3-Az9 Sweep Fluid (y)	Mixed Fluid (y)
Infinite	484	297	5180	503
Circular	202	173	2110	165
Step	224	191	2320	206
Exponential	159	114	1720	67
Normal	182	153	1910	118

Table 2
Heat Extraction by Reinjection Recharge

Assumed Temperature Distribution	La Primavera PR2-PR1 Heat Content (10^{18}J)	Heat Extr'd (10^{18}J)	Fractn Extr'd (%)	El Chino Az3-Az9 Heat Content (10^{18}J)	Heat Extr'd (10^{18}J)	Fractn Extr'd (%)
Circular	30.9	0.296	0.96	52.2	0.511	0.98
Step	28.9	0.347	1.20	48.6	0.595	1.22
Exponential	28.7	0.197	0.69	48.3	0.349	0.72
Normal	28.7	0.248	0.86	48.4	0.429	0.89

the more rapidly declining exponential distribution. The heat content for the circular reservoir with rapid temperature falloff after 25 crescents is somewhat greater than the others with 31 crescents to abandonment temperature. The heat extraction varies as the distribution type, ranging from about 0.7 to 1.2 percent.

The data for the El Chino case reflects the difference in sweep reservoir volume and reinjection rate with much longer cooldown times. The range for all of the initial temperature distributions is less than half of the 5000 years observed for the infinite uniform temperature distribution. The relative times for the four initial temperature distributions are about the same as for the La Primavera doublet. The circular reservoir again shows a cooldown time between those for the step and normal distributions and the normal distribution between those for the step and exponential distributions. The heat content calculated for this larger flow doublet is correspondently larger. The heat extracted by recharge return flow sweep is also larger with about the same fractional extraction of thermal energy. The relative similarity in the heat sweep for these two doublets may be due to the similar reservoir properties for fracture spacing, porosity, and initial temperatures.

CONCLUSIONS

In a geothermal reservoir with a large separation distance between injection and production wells relative to the reservoir mean fracture spacing, and with no apparent flow boundaries, the doublet return flow serves as a reasonable flow geometry for the well pair system. In unexploited geothermal resources, the initial temperature distribution for the whole reservoir is generally not known. In such cases the assumption of an initial temperature distribution becomes necessary. This study showsthat the assumption of a fractured-rock reservoir with temperature normally distributed away from the production well zone results in estimated cooldown times with enhanced energy recovery smaller than those estimated for an extended uniform temperature distribution. The estimated cooldown times also fall between those for the larger heat content of the step distribution and the exponential temperature decline. The corresponding results in terms of heat extraction from theformation can be estimated from the given reservoir thermophysical properties. The two case studies with available preproduction data show the relative cooldown times for these initial temperature distributions compared to the results with the assumption of an infinitely uniform temperature distribution. In contrast to the almost complete extraction of the heat content above the abandonment temperature for the small and well-defined linear and radial flow geometries, the doublet flow geometry with its essentially infinite expanse and very large heat content, shows a very small heat extraction fraction (of the order of one percent in the cases studied) as reinjection recharge fluid at the injection temperature breaks through in the shortest crescents.

REFERENCES

Grove, D.B., Beetem, W.A., and Sower, F.B., Fluid Travel Time between a Recharging and Discharging Well Pair having a Uniform Flow Field, Water Res. Res. 6, 1404-1410 (1970).

Hunsbedt, A., P. Kruger, and A.L. London, Energy Extraction from a Laboratory Model Fractured Geothermal Reservoir, J.Petrol.Tech., 30, No.5, 712-718 (1978)

Hunsbedt, A., Lam, S.T., and Kruger, P., User's Manual for the 1-D Linear Heat Sweep Model, Report SGP-TR-75, Stanford Geothermal Program, Stanford University, 1984.

Iregui, R., A. Hunsbedt, P. Kruger, and A.L. London, Analysis of Heat Transfer and Energy Recovery in Fractured Geothermal Reservoirs, Report SGP-TR-31, Stanford Geothermal Program, Stanford University, 1978.

Kruger, P., The Role of Heat Sweep in Reinjection of Cooled Geothermal Fluids, Geotermia, 4, 247-253 (1988).

Kuo, M.C.T., P. Kruger, and W.E. Brigham, Shape-Factor Correlations for Transient Heat Conduction from Irregular-Shaped Rock Fragments to Surrounding Fluid, Paper 77-HT-54, AIChE-ASME Heat Transfer Conference, ASME, August, 1977.

Lam, S.T., Chapter 6 (1986) in PhD Thesis (in preparation).

Lam, S.T. and Kruger, P., 1-D Doublet Heat Sweep Model, Proceedings, 9th NZ Geothermal Workshop, (University of Auckland, NZ, November, 1987)

Maciel, R., La Primavera Geothermal Field, CFE, Guadalajara, Mexico, private communication, 1988.

Stehfest, H., Numerical Inversion of the Laplace Transform, Algorithm No. 368, Comm.ACM, 13, No.1 47-49, 1970.