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COMPARISON OF THERMAL COOLDOWN ESTIMATES IN THE RUSSKIE KOMAROVTSY PETROGEOTHERMAL RESERVOIR

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ABSTRACT

A comparison of several models to estimate the rate of thermal cooldown in artificial circulation geothermal reservoirs was made for the Russkie Komarovtsy fracture-stimulated reservoir, which will be located near the town of Uzhgorod in the Zakarpate region of the Ukraine SSR. The economic viability of this moderate-temperature resource depends on sustained flow above the minimum abandonment temperature for a period sufficient to recover investment and operating costs. The rate of heat extraction for the required flowrate depends on the fracture distribution in the reservoir. Results of the SGP 1-D Heat Sweep model are compared to approximate analytical and numerical models developed at the Leningrad Mining Institute, based on a common set of initial conditions for the Russkie Komarovtsy reservoir. The comparison shows that all of the models yielded reasonably similar thermal decline estimates with a satisfactory lifetime of about 25 years to abandonment temperature.

INTRODUCTION

Commercial development of the extensive, widely distributed petrogeothermal resources in the world depends on attaining economic efficiency in heat extraction from natural and artificially-fractured geothermal reservoirs by circulation of water as a heat-carrier fluid. Methods to predict the rate and lifetime of heat extraction from these moderate-temperature resources are very important for early decisions affecting their long-term development in the USA, USSR, and other countries seeking alternate sources of indigenous energy. The ability to develop commercial technology for heat-extraction at a sufficient rate over a satisfactory amortization period requires understanding of the complex heat and mass transfer processes involved. Heat transfer in fractured petrogeothermal reservoirs is a very complicated process (Dyadkin, 1989) dependent on a combination of geometric parameters of reservoir structure, hydrologic flow regimes, production and reinjection practices, and thermal properties of the fractured-rock formation. Pre-production data for many of these parameters are generally sparse, and heat extraction predictions for specific potential projects must be made from best estimates and suitable models of the geothermal system.

The economic feasibility of energy extraction from fracture-stimulated reservoirs with artificial circulation systems has been estimated (e.g., Boguslavsky, 1981; Murphy, et al, 1985; Dyadkin, 1985) with many assumptions concerning the processes of unsteady, non-isothermal flow of circulating fluid through a reservoir of fracture and matrix permeability distributions and of heat transfer rates for planar and irregular shaped rock blocks. Models have been developed for estimating heat extraction from such reservoirs (e.g., Gringarten, et al, 1978; Hunsbedt, et al, 1979; Pruess, 1983; Dyadkin and Gendler, 1985). In view of the need to improve the ability of heat extraction models to predict the behavior of yet undeveloped resources based on available data, a comparison was made between models developed at the Leningrad Mining Institute with the model developed at the Stanford Geothermal Program. The LMI heat-physics models, described by Smirnova (1978); Artemieva (1979a,1979b); Gendler and Pavlov (1980); Mukhin and Smirnova (1981); Artemieva and Piskacheva (1983); Dyadkin and Gendler (1985); and Artemieva and Stroganova (1986), were developed for several thermal aspects of mining operations. The SGP 1-D Heat Sweep model, described by Hunsbedt, et al (1977,1978,1979); Kuo, et al (1977); Kruger (1982); Hunsbedt, Lam, and Kruger (1983); and Lam and Kruger (1988), was developed for early analysis of prospective geothermal reservoirs based on pre-production data for estimating thermal recovery from reinjected fluid as a function of production strategy and reservoir characteristics.

To estimate the extent of uncertainty in modeling thermal extraction in an artificial circulation system, the 1-D Heat Sweep model has been compared with other heat extraction models, such as the LBL Reservoir Simulator (Lam, et al, 1988) and the Fenton Hill Hot Dry Rock reservoir model (Robinson and Kruger, 1988). As a basis for comparison of the LMI physical and numerical models with the SGP 1-D model, a test case was made of the Russkie Komarovtsy geothermal prospect, which is planned to be the first experimental demonstration of a moderate-temperature petrothermal resource created by hydrofracturing stimulation as an artificial circulation system. This case was chosen to examine the reliability of estimating lifetimes of moderate-temperature petrogeothermal resources, where the production time to reach abandonment temperature at the required flowrate is critical for providing a reliable and economic heat source.

RUSSKIE KOMAROVTSY GEOTHERMAL FIELD

The prime candidate for the first demonstration project of economic heat extraction from moderate-temperature petrogeothermal resources prevalent in the USSR is the Russkie Komarovtsy field in the Zakarpate region of the Ukraine SSR. This site was selected from an initial list of 16 candidate sites compiled from a national survey of USSR regions for a GeoTES (geothermal heat energy station) to provide a hot-water supply for municipal and agricultural heating. The demonstration project is designed to produce thermal water through a connected network of three large parallel hydrofractures at a constant flowrate, augmented by fossil-fuel heating, if necessary, over a useful lifetime in excess of 10 years.

Figure 1 shows a schematic section of the reservoir after five phases of reservoir creation by hydraulic fracturing. The resource consists of a massive granodiorite intrusive of 740 m thickness at a mean temperature of 124 °C, situated almost horizontally at a depth of 1900 to 2640 m. A description of the geologic setting was given by Vainblat and Drozdetskaya (1987). The hydrofracturing scheme was designed by Dyadkin (1987) and co-workers and the economics of heat extraction were estimated by Boguslavsky (1987). Early estimates of the fracture geometry were described in Dyadkin and Kruger (1989). Dyadkin, in 1990, provided updated estimates of the anticipated hydrofracturing results and comparative analyses of the heat extraction are based on the revised dimensions of the reservoir and planned flowrates to achieve economic return.

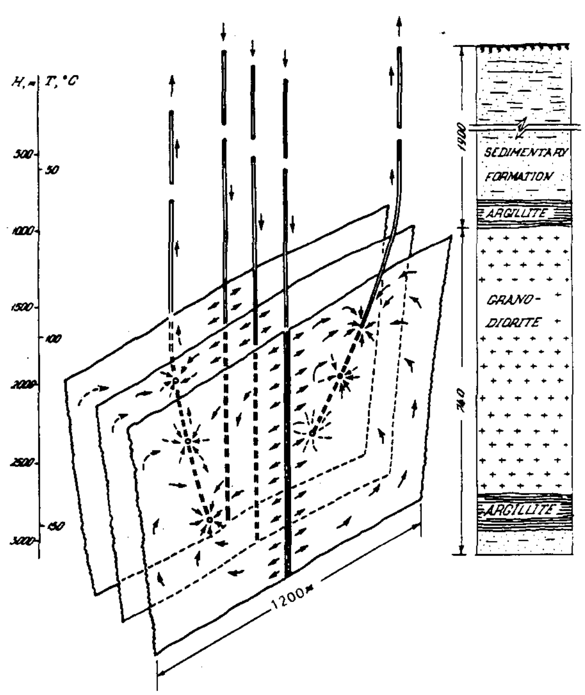

Fig. 1. Schematic of the Russkie Komarovtsy two-wing, three-parallel hydrofractured reservoir. (from Dyadkin and Kruger, 1989).

The three parallel-fracture reservoir will have an extractable heat content of HC = 9.88×10^{15} J for thermal drawdown from the mean initial temperature of 124 °C to the abandonment temperature of 110 °C. For a 10-year production lifetime at the anticipated flowrate of 11 kg/s per fracture, the mean heat extraction rate would be about 3130 kJ/s. The set of input data common to the comparison runs by the LMI and SGP models is listed in Table 1. Data specific for rock mechanical properties in the heat physics models are given in the respective publications.

THE LMI HEAT EXTRACTION MODELS

Analytical and numerical heatphysics models have been developed at LMI (Dyadkin and Gendler, 1985) for thermal mining processes over a number of years. An approximate analytical solution for bottom-hole fluid temperature after heat transfer in a vertically fractured rock to circulating fluid was examined by Smirnova (1978). The approach to the problem was adopted from Lauwerier (1955) for heat transport in an oil layer with injection of hot water. The method of Lauwerier is discussed by Prats (1986). The solution of the governing equations was derived with double application of the Laplace transform, first with respect to distance into the layer, and second with respect to time. The back transforms (from Carslaw and Jaeger, 1948) was of the form of the complimentary error function for the dimensionless fluid temperature:

$$\theta_f = \frac{T_r - T_f}{T_r - T_i} = erfc\frac{1}{\sqrt{J}} \qquad (1)$$

$$J = \left[\frac{Q_f C_w \rho_w}{W_f L_f}\right]^2 \frac{t - \frac{W_f L_f \delta}{Q_f}}{\lambda C \rho} \qquad (2)$$

where
T_r = mean initial formation temperature, °C
T_f = production well bottom-hole fluid temperature, °C
T_i = injection well bottom-hole fluid temperature, °C
ρ, ρ_w = density of rock, water, kg/m^3
Q_f = water flow rate in fracture, m^3/s
W_f, L_f = width, length of fracture, m
δ = mean fracture aperture, m
C, C_w = specific heat capacity of rock, water, J/kg°C
λ = thermal conductivity of rock, W/m°C
t = time, sec

If $t \gg (W_f L_f \delta)/Q_f$, then the dimensionless temperature in Equ. (1) can be approximated by the Austin formula in Gringarten, et al (1978) as

$$\theta = erfc\left(\frac{L_f W_f}{Q_f \rho_w C_w}\sqrt{\frac{\lambda \rho C}{t}}\right) \qquad (3)$$

Dyadkin and Gendler (1985) note that the approximation is correct for the relationship of modified Grashof number to Reynolds number over the range

Table 1
Russkie Komarovtsy Modeling Data Set

Parameter	Value	Parameter	Value
Reservoir Characteristics		Thermal Properties	
Rock Type: Granodiorite		Rock Density	2650 kg/m³
Dimensions		Rock Specific Heat	1000 J/kg°C
Length	1200 m	Thermal Conductivity	2.1 W/m°C
Width	300 m	Water Density (mean)	945 kg/m³
Height	740 m	Water Specific Heat	4200 J/kg°C
Mean Frac. Spacing	variable		
Porosity	0.00066		
Production Characteristics			
Initial Temperature	124 °C		
Injection Temperature	30 °C		
Abandonment Temp	110 °C		
Circulation Flowrate	36.9 kg/s		

$0 < (Gr^*/12\ Re) < 12$, where the two numbers are defined as:

$$Gr^* = \frac{g\alpha_f \Delta T_f \Delta L_f \delta^2}{\mu^2} \qquad (4)$$

$$Re = \frac{W_f}{\delta}\mu$$

where
g = gravitational constant, 9.81 m/s²
α_f = thermal expansion coefficient for water, °C⁻¹
ΔT_f = temperature change across fracture length, °C
ΔL_f = fracture length between well pair, m
δ = fracture aperture, m
μ = fluid viscosity, Pa.s

The LMI numerical model was developed by Artemieva (1979a,b) from consideration of the stability of a non-uniformly heated fluid flowing in a horizontal fracture. The approach was based on the use of Rayleigh and Peclet numbers in appropriate ranges, determined numerically. The modified Rayleigh number is derived from injection parameters and the Peclet number accounts for non-uniform permeability and temperature dependence of fluid viscosity. Dyadkin and Gendler (1985) note that the investigation of the heat exchange process in fractured rock was given in Artemieva and Piskacheva (1983). Numerical solution of the hydrodynamic equations was carried out for vertical rectangular fractures of constant aperture. Results of the numerical calculations confirmed the basic conclusions reported by McFarland (1975) for the Fenton Hill hydrofractures as estimated at that time. It was also noted that the numerical solution was satisfied for the range of modified Grashof and Reynolds number criteria adapted for the analytical model.

THE SGP 1-D HEAT SWEEP MODEL

The 1-D linear heat sweep model was initially developed for analysis of experimental measurements of heat extraction from an assembly of arbitrary-shaped rock blocks in a laboratory model of a fractured-rock reservoir (Hunsbedt, et al, 1977). The model has been improved to provide for radial and doublet flow (Lam, 1989) and for non-uniform initial temperature distribution (Lam and Kruger, 1988). The differential equations which describe heat transfer from an assembly of rock blocks with a single mean equivalent-sphere radius to the surrounding fluid in linear heat sweep circulation are given in Kruger (1982). The nondimensional fluid temperature at location x and time t, can be expressed in terms of three parameters: N_{tu}, γ, and q,

$$T_f^*(x^*, t^*) = \frac{T_f(x,t) - T_e}{T_i - T_e} = f(N_{tu}, \gamma, q) \qquad (5)$$

where
x^* = x/L, nondimensional linear distance from injection well to production well
t^* = t/t_{res}, nondimensional flow time
N_{tu} = τ/t_{res}, number of heat transfer units, given by the ratio of the thermal time constant of the rock blocks to the mean residence time of the fluid
γ = thermal storage ratio, thermal energy stored in the surrounding fluid relative to that in the rock blocks
q = external heat transfer parameter per unit flow path length.

The "number of heat transfer units" parameter indicates the relative thermal aspects of the flowing reservoir, based on anticipated flowrate through the fracture flow path. For small values (N_{tu} < 10), the reservoir is heat transfer limited. The rate of heat conduction to the rock block surfaces is insufficient for effective heating of the circulating fluid, resulting in rapid decline in produced water temperature.

Fig. 2 shows the equivalent flow geometry for the Russkie Komarovtsy three parallel hydrofractured reservoir as a one-dimensional linear heat sweep problem. The model considers the question as two independent flows through 600 m of fracture path length with various values of mean fracture spacing. With the LMI assumption of fully competent rock without

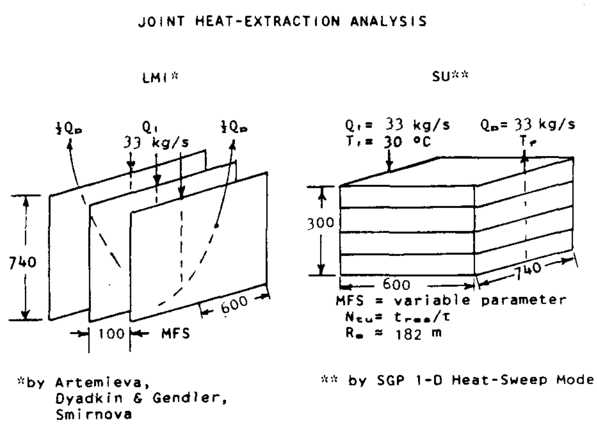

Fig. 2. Equivalent flow geometry for one wing of the Russkie Komarovtsy reservoir for 1-D linear heat sweep modeling.

natural fractures following hydrofracturing, the volume of each rock block would be $V_b = 600 \times 100 \times 740 = 4.44 \times 10^7\ m^3$ and the equivalent heat transfer spherical radius would be $R_e = \phi_K (3V_b/4\pi)^{1/3} = 182$ m. The thermal time constant of the rock block is

$$\tau = R_e^2/3\alpha\ (0.2-1/Bi) \qquad (6)$$

where

ϕ_K = Kuo sphericity (Kuo, et al, 1977) = 0.83

α = thermal diffusivity of the rock

Bi = Biot number of the rock

For an equivalent radius of 182 m, the time constant is 88.7 years. Based on the LMI estimated minimum required flowrate of 11 kg/s per fracture to achieve economic thermal energy extraction, the mean residence time would be 0.08 years (29 days). The "number of heat transfer units", thus for any such flowrate would be of the order of 0.001, much too small for effective heat extraction rate. Therefore, in estimating the Russkie Komarovtsy reservoir production, it was assumed that natural fractures would exist as flow paths, and calculations were made for a range of mean fracture spacings from 50 m (R_e = 25 m, with a correspondingly smaller thermal time constant).

RESULTS

Fig. 3 shows the cooldown results calculated by the LMI analytical model (solid lines) and the LMI numerical model (dashed lines) as a function of flowrate through the main hydrofractures. The values from 5.5 to 50 kg/s per fracture represent the range of needed flowrates for economic return. For a flowrate of 11 kg/s per fracture, the analytical model predicts a lifetime of 25 years to the abandonment temperature of 110 °C.

Fig. 4 shows the corresponding cooldown estimates calculated by the SGP 1-D heat sweep model for competent rock blocks with MFS of 354 m for an

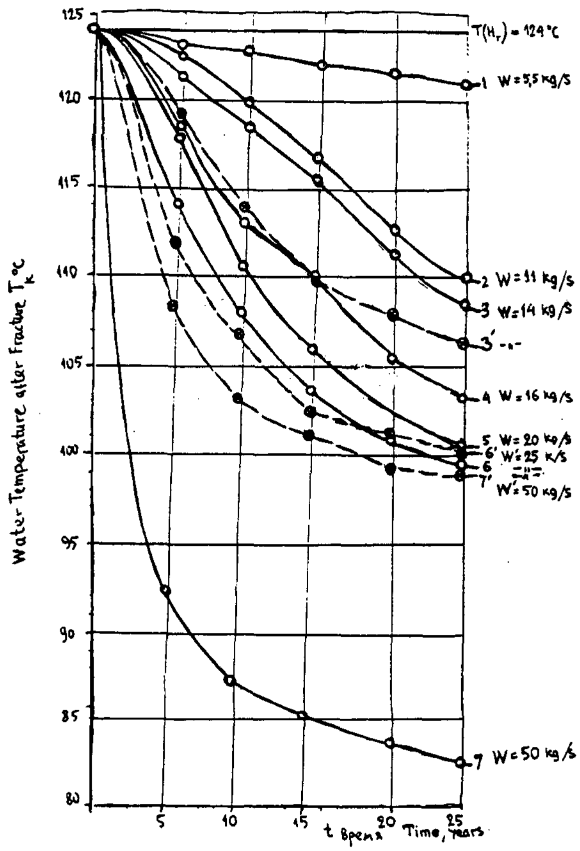

Fig. 3. Results of LMI cooldown estimates as a function of flowrate through the principal hydrofractures by the numerical model (solid lines) and the analytical model (broken lines). (hand carried from LMI by Y. Dyadkin, September, 1990)

equivalent radius of 182 m. The values for flowrate of 5.5 and 11 kg/s per fracture show cooldown to abandonment temperature in less than two years. Larger flowrates would result in even faster cooldown to 110 °C. Fig. 5 shows the calculated cooldown for a flowrate of 11 kg/s per fracture as a function of mean fracture spacing. For MFS values around 50-100 m, cooldown to 110 °C would be longer than 25 years, and above 200 m, the cooldown time would be less than 10 years, the minimum amortization period. A match with the LMI analytical method for the anticipated flowrate of 11 kg/s per hydrofracture occurs for a MFS of about 160 m.

Table 2 gives a summary of the cooldown results for the range of flowrates considered. The values for the LMI analytical model agree well with the LMI numerical model for flowrates of 14 and 25 kg/s, but differ somewhat for 50 kg/s. The SGP model shows the very rapid temperature decline for the assumption of MFS = 354 m (τ = 88.7 y) for competent rock blocks after hydrofracturing. The small value of 50 m (τ = 1.77 y) shows adequate heat transfer with essentially no cooldown for 10 years at flowrates up to about 25 kg/s per fracture and possibly sustained production at

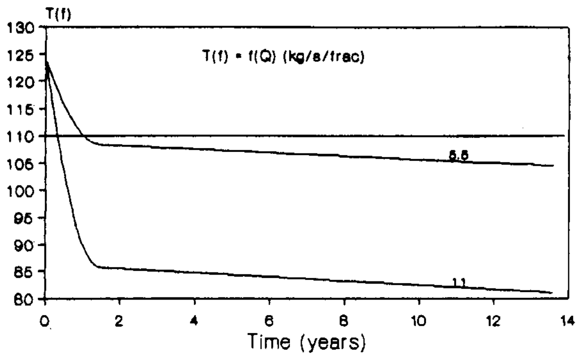

Fig. 4. Results of SGP cooldown estimates as a function of flowrate around the hydrofractured rock blocks with equivalent radius of 182 m.

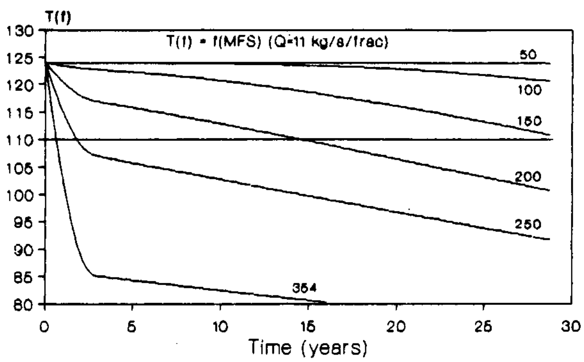

Fig. 5. Results of SGP cooldown estimates as a function of mean fracture spacing for the LMI anticipated flowrate of 11 kg/s per hydrofracture.

Table 2
Comparison of LMI-SGP Calculated Results

	Bottom-hole Fluid Temperature (°C) after 10 years of Production				
	LMI Model		SGP MFS (m)		
Flowrate (kg/s/fracture)	Numerical	Analytical	354	160	50
5.5	123	--	106	124	124
11.0	120	--	83	120	124
14.0	118	114	--	115	124
16.0	113	--	--	110	124
20.0	111	--	--	104	124
25.0	108	107	--	97	123
50.0	87	103	--	72	108

50 kg/s for almost 10 years. At the match MFS of 160 m ($\tau = 18.1$ y), the calculated values follow those of the LMI models at flowrates to about 20 kg/s and decline faster thereafter.

DISCUSSION

The comparison of the two LMI models and the SGP model has pointed out some key aspects with respect to the resulting hydrodynamic regime for heat extraction by a circulating fluid. Foremost of these is the actual results of the massive hydraulic fracturing which creates the artificial reservoir. The possibilities of creating competent parallel hydrofractured blocks without associated interconnections through opened natural fractures is discussed by Dyadkin, et al (1990). It is apparent that independent means (such as seismic response or tracers) to ascertain the actual volume and heat content of the fractured rock constituting the reservoir is needed. A second key aspect is the actual flow paths taken by the injected fluid. The three models assume the flow is uniformly distributed, and in the LMI models, primarily in the hydrofractures. The rate of heat transfer with distance between wells and time is thus strongly influenced by the flow and initial temperature distributions. A third aspect is the induced changes in the reservoir with production time. Fracture patterns and rock thermal properties are likely to change with temperature and pressure changes over the lifetime of the reservoir. Since each of these aspects is unknown during the planning and initial production phases at a newly created petrogeothermal resource, the ability to estimate possible ranges of productivity becomes very important. When estimates made by models of diverse assumptions provide a reasonable range of potential results, the confidence level of making investment decisions rises markedly. Although many differences exist between the LMI analytical and numerical models and between the LMI and SGP models, the agreement in range of expectations is sufficiently good to consider that given the large uncertainties in the above mentioned aspects of heat extraction, the estimated lifetime of the Russkie Komarovtsy petrogeothermal resource should provide the minimum return of hot water supply at the required flowrate for a minimum of 10 years and likely for 25 years without the need for fossil-fuel augmentation.

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