PROCEEDINGS, Fifteenth Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, January 23-25, 1990
SGP-TR-130

PRELIMINARY ANALYSIS OF TRACER RESPONSE AND THERMAL COOLDOWN ESTIMATES FOR THE MUTNOVSKY GEOTHERMAL FIELD IN KAMCHATKA, USSR

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ABSTRACT

A fluorescein tracer injection test was carried out at the Mutnovsky geothermal field in Kamchatka, USSR to evaluate reservoir characteristics in preparation for the construction of a 50-MWe power plant. The test consisted of a 6-hour pulse tracer injection in an observation well very close to two production wells, followed by four weeks of fluid reinjection from one of the nearby wells, with monitoring at several wells in the production zone. A joint study is underway to combine analysis of the tracer response and simulated thermal cooldown based on the very close-spaced flow geometry and estimated thermal properties of the reservoir. The results show both rapid tracer breakthrough and a rapid thermal decline transient. The test provided improved estimates of the effective reservoir porosity and reservoir thickness. The comparison of the tracer-test data with the simulated heat-sweep estimates are reviewed in the paper.

INTRODUCTION

Development of hydrothermal resources in the Kamchatka Peninsula is proceeding with the planned construction of a 50-MWe geothermal power station at the Mutnovsky geothermal field near the population center at Petropavlovsk. The Mutnovsky hydrothermal system as described by Kiryukhin and Sugrobov (1987) is located in the northern foothills of the Mutnov volcano and is marked with surface manifestations of boiling hot springs and saturated steam vents. The geologic structure of the hydrothermal system is very complex, contained in a tectonic zone of intersecting fractures in a north-easterly direction, bounded by the ancient Zhirov volcano to the east, the caldera of the Gorel volcano to the west, and the Mutnov volcano to the south. A sketch of the region is shown in Figure 1. The production zone is in the Dachny area in the center of the sketch on the C'-C section line. The hydro-thermodynamic model of the system (by Kiryukhin and Sugrobov, 1987) uses the network of grid blocks shown in Figure 2, with meridional prisms simulating the Northern-Mutnovsky tectonic zone, latitudinal prisms for the Gorel zone of tectonic fractures, inclined prisms for the north-east fault strike, and right cylinders for the caldera of the Gorel volcano.

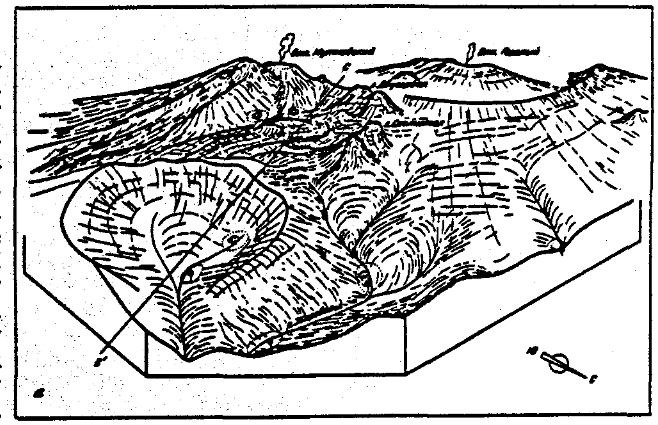

Fig.1 Sketch of the Mutnovsky geothermal region in Kamchatka. The C'-C section cuts across the Zhirov volcano, the Dachny (central resource) area, and the Mutnovsky volcano. The Gorel volcano is to the west. The valley of the Zhirov River is in the foreground.

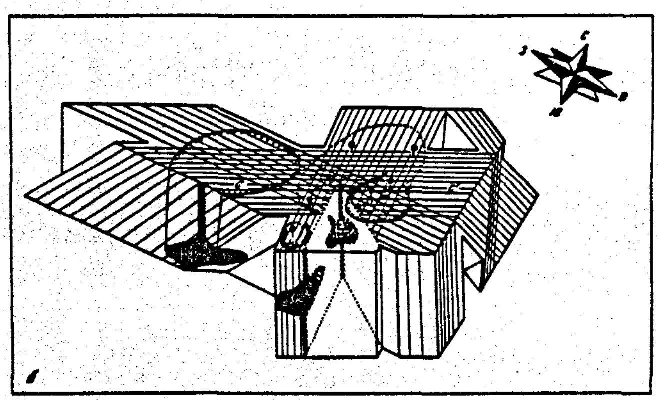

Fig.2 Block diagram of the Mutnovsky hydrothermal system for the simulation models, showing the main fracture systems.

The hydrothermal activity is manifested by energetic release of steam from active sinkholes and many steam vents in the North Mutnovsky zone and Zhirov River valley. Heat emission from the sinkholes by steam with temperature of 500-700 °C reaches 400,000 kcal/s. The steam vents in the northern crater of the Mutnovsky volcano release about 93,000 kcal/s at maximum temperature of 305 °C. The boiling vents in the Zhirov and Mutnov River valleys release 3,800 kcal/s of superheated water (Nizhnezhirovsky vents) and 2,000 kcal/s of hot water at 93 °C (Voinsky vents).

Exploratory drilling was initiated in the central part of the Mutnovsky geothermal field (Dachny section) to confirm the occurrence of superheated water and steam in the underground system. Well were drilled through the steam cap, steam condensation zone, and into the zone of boiling water. Bottom-hole temperatures, by geochemical thermometers, heat flow, and direct measurement reached 272 °C. The heat flux in the North-Mutnovsky zone was estimated from the thermal discharge (30,800 kcal/s) and the area of the thermal anomaly (48 km^2) as 2.7 W/m^2. For the estimated volume of the North-Mutnovsky geothermal reservoir of 120 km^3, with an extraction rate of 6.2 x 10^8 J/s, the potential extractable energy for a geothermal electric generating station was estimated to be between 30,000 and 45,000 megawatt-years.

A simple model was developed (Kiryukhin and Sugrobov, 1987) to evaluate the hydrothermal systems in Kamchatka suitable for producing steam for electric power plants and hot-water supply systems. An early application of the model was the study of the flow regime from pressure drawdown data at the operating geothermal power station at the Pauzhetka geothermal field was given by Kiryukhin (1988). Thermal drawdown of the Pauzhetka field was examined by Kiryukhin (1984).

The thermohydrodynamic model is being used to evaluate the hydrothermal potential of the Mutnovsky geothermal field. A summary of the input data for the model calculations is given in Table 1.

The results of the calculations provide a time series of cross sections of the temperature and flow regime across the thermal anomaly starting with the inner block at an initial temperature of 700 °C and given infiltrating fluid flow rate. The natural state after 63,000 years shows a thermal core of over 430 °C at a depth of 10 km and a general mean temperature of about 270 °C at 8 km.

To obtain an early evaluation of the reservoir characteristics of the field for field development purposes, a tracer test was performed in August-September, 1989 by injection of fluorescein dye into a central observation well in the field with monitoring at nearby production wells. At the same time, an estimate of the thermal cooldown was made with the same values of the thermal properties of the system and the same flow conditions to compare the observed tracer response to the estimated thermal response of the reservoir around the test wells. This paper presents an initial evaluation of the results of the observed tracer response data and the calculated thermal cooldown to the closest production wells for radial recharge flow in an assumed horizontally recharging formation.

THE MUTNOVSKY TRACER TEST

The tracer test was initiated on 7 August 1989 with injection of 8 kg of fluorescein dye over a six-hour period into observation well 029DV located about midway between production wells 1 and 011. A plan view of the test wells is given in Figure 3. The production flow from well 1 of about 10 kg/s was reinjected into well 011 as the tracer-carrier fluid through the reservoir. Reinjection was continued through 9 September 1989 for a total period of 33 days. Tracer concentration and wellhead fluid temperature data were collected at wells 1, 03, 013, 014, and 24 during the flow period. Well 03 was flowed during the test period only to collect samples. The fluorescein

Table 1
Input Data for the Mutnovsky Hydrothermal System Model*

Parameter	Value
1. Geometric Size of the Flow Regime	
Depth	15 km
Width	5 km
2. Thermal Properties	
Coefficient of Heat Conduction	2.09 W/m°C
Geothermal Gradient	0.015 °C/m
3. Filtration Parameter	10-110 m^2/day
4. Modeling Time Period	63,000 years
5. Heat Source	
Dimensions (area of section)	40+20, 64+40, 120+80 km^2
Initial Temperature	700 °C
Depth of Overlying Cap	6 and 5 km
6. Infiltration Flux (mean value for flow reg.)	2.5-10.0 kg/s.m^2

* from Kiryukhin and Sugrobov (1987)

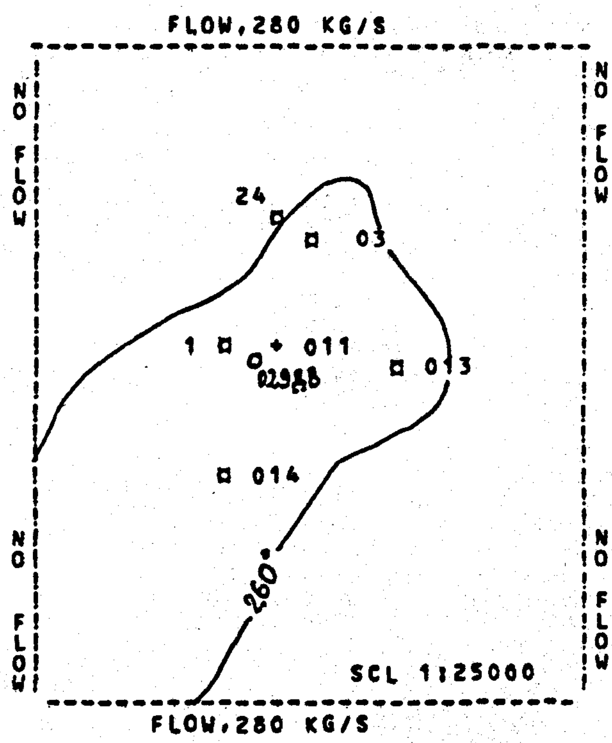

Fig.3 Plan view of the Mutnovsky geothermal field, showing the location of the production zone within the 260 C isotherm at depth and the location of the tracer injection well, 029DV.

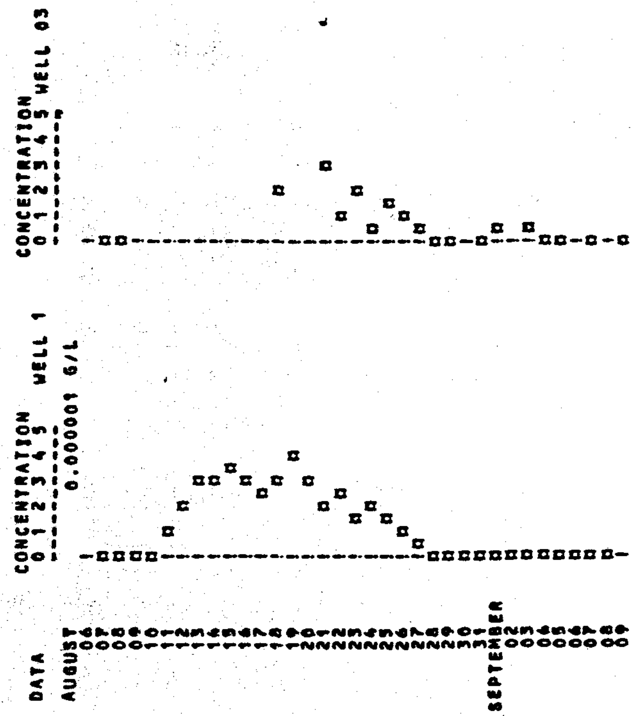

Fig.4 The Fluorescein tracer response data for well 1, just west of the injection well, and well 03, nne from the injection well.

concentration data as wired to Stanford on 12 September 1989 are shown in Figure 4. It is noted that the precision of measurement is 0.5 µg/l. The data for the nearby well 1 (160 m) show a breakthrough time of about 4 days and for the more distant well 03 (400 m), the time is less than 12 days, when the first above-background sample was taken. Peak concentrations are at 9 to 12 days for well 1 and about 12-14 days for well 03.

The Institute of Volcanology text included the observations that there was no tracer response in wells 013, 014, and 24 and that the total mass of fluorescein extracted from well 1 was only 40 g, (0.5 %). Based on the geologic framework of the inner production zone, consisting of tuffs around well 1 and tuffs and sandstones around well 03 with a mean thickness of 280 m, the tracer test is initially interpreted as indicating a natural flow in the reservoir with a north-north-east direction. From the simple expression of volumetric flow in a 2-D right cylinder for the well pair 011 to 1,

$$V = Qt = \phi \pi r^2 h$$

the porosity, ϕ, is estimated as 0.00023, for a mean flowrate of $Q = 0.01$ m^3/s, mean time of $t = 12$ days, distance between wells of $r = 160$ m, and reservoir thickness of $h = 280$ m. The velocity of natural flow from well 011 to observation well 03 is estimated from $v = L/t$ as 28.5 m/s for the distance between wells of $L = 400$ m and maximum tracer peak time of $t = 12$ days. Finally, the mass rate of natural flow is estimated by

$$Q(n) = \phi(\rho w h)v$$

as $Q(n) = 280$ kg/s for fluid density $\rho = 770$ kg/m^3 and mean flow width $w = 200$ m.

THERMAL COOLDOWN ESTIMATES

To predict thermal cooldown during the tracer test, the SGP 1-D Heat Sweep Model, developed by Hunsbedt, Lam, and Kruger (1984), was used to estimate the bottom-hole fluid temperature at the monitoring wells. Based on no injection fluid loss, the produced fluid was taken as a mixture of the tracer-carrier fluid injected into well 011 from well 1, with heat sweep along its return flow path, and production-flow makeup from deeper resource fluid at initial reservoir temperature of 270 °C, taken as the mean temperature for the production area enclosed by the 260 °C isotherm shown in Figure 3. Values for the formation thermal properties were compiled during meetings in Leningrad prior to the tracer test. Values for reservoir thickness and mean fracture porosity were taken from the tracer test results. For the short distances between the injection and the two production wells, small-angle radial flow through large-sized fractured rock blocks was assumed to be the most likely geometry for heat transfer. The data for the heat sweep cooldown estimates are given in Table 2.

Table 2
Input Data for the Tracer-Test Heat-Sweep Estimates

Parameter	Value
Initial Reservoir Temperature	270 °C
Recharge Fluid Temperature	93 °C
Reinjection Flowrate	10 kg/s
Well 011 Production Flowrate	12 kg/s
Reservoir Properties	
Mean Thickness	280 m
Injection Well Radius	0.05 m
Well 1, 03 Distance	160, 400 m
Flow Angle	small
Mean Reservoir Porosity	0.00023
Mean Fracture Spacing	variable
Formation Thermal Properties	
Rock Density	2350 kg/m^3
Specific Heat Capacity	1070 J/kg°C
Thermal Conductivity	2.09 W/m°C
Fluid Density	854 kg/m^3
Specific Heat Capacity	4870 J/kg°C
Heat Transfer Coefficient	1700 W/m^2 °C

The cooldown simulations for the two well pairs over the 30-day test period are illustrated in Figures 5 and 6 for both variable radial flow angle and mean fracture spacing. In the SGP 1-D Heat Sweep Model, the return flow angle represents the mean residence time of the injected fluid and the mean fracture spacing represents the thermal constant of the formation rock blocks. The results for the closer well pair, 011 - 1, show significant early thermal cooldown for return flow angles of less than 60 degrees and for mean rock block spacing of more than 25 m. For flow in the indicated north-north-east direction between wells 011 - 03, corresponding values are about 15 degrees and 50 m. A summary of the bottom-hole sweep-fluid temperature at 14 days following tracer injection for the range of return-flow angle and mean fracture spacing conditions is presented in Table 3.

DISCUSSION

The Mutnovsky geothermal field has been described as a very complex hydrothermal system because of the many natural-fracture networks traversing the aquifer system. Modeling of the field by Kiryukhin and Sugrobov (1987) has left many unresolved questions about the reservoir properties of the system. The tracer test conducted in the Fall, 1989 provided additional information on the reservoir fracture porosity, reservoir thickness, and natural flow direction. With the design of the test based on tracer flow within the central part of the reservoir, it is not surprising to observe the short times of first arrival and the relatively early arrival of the peak concentration. Injection of the tracer into an observation well in the central part of the reservoir, midway between the nearby injection well 011 and production well 1 results in an initial ambiguity of flow geometry. The low precision of the fluorimeter also provided some ambiguity, especially in the timing of first and peak arrivals. The lack of tracer return to several of the flowing wells indicated an anisotropic return flow geometry, apparently oriented in the prevailing north-north-east fracture direction. The small total tracer return of only 0.5 % at the close-by well 1 may indicate a significant loss of tracer, possibility by downward flow of the cooler tracer fluid below the production horizon of the wells, no fracture connections, thermal degradation of the fluorescein, or retardation in the tuffaceous formation.

However, based on simple 2-D horizontal flow in conjunction with information obtained from other means, several reservoir parameters can be roughly estimated. For a reservoir mean thickness of 280 m, the mean fracture porosity has been estimated as 0.00023, indicating a tightly packed block structure with small fracture apertures. Linear flow these fractures appears to be very rapid, as observed by the tracer response curves. The rapid appearance of tracer at well 03 some 400 m from the reinjection well 011 and the non-appearance of tracer at well 24 may indicate a large natural flow through the n-n-e aligned fracture system. The natural flow through the reservoir may be of the order of 280 kg/s.

The heat-sweep simulations also provide some insight into the reservoir conditions. The thermal transient for well 1 is about 2-4 days for the given flow conditions, which corresponds to the time of first arrival of the tracer front from well 029DV, located about halfway between injection well 011 and production well 1. The more rapid transient

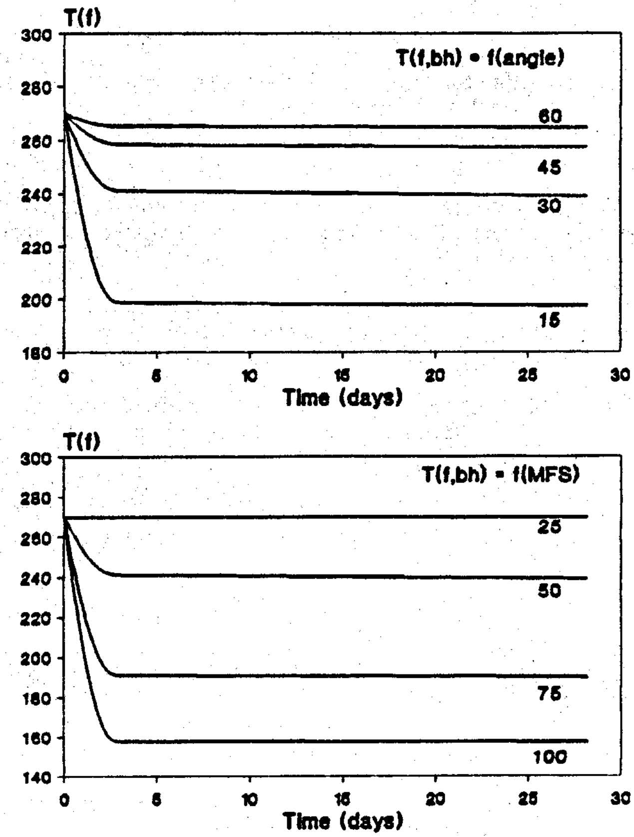

Fig.5 Cooldown curves for Well Pair 011-1 for the tracer-test period as a function of return-flow angle (upper) and mean fracture spacing (lower).

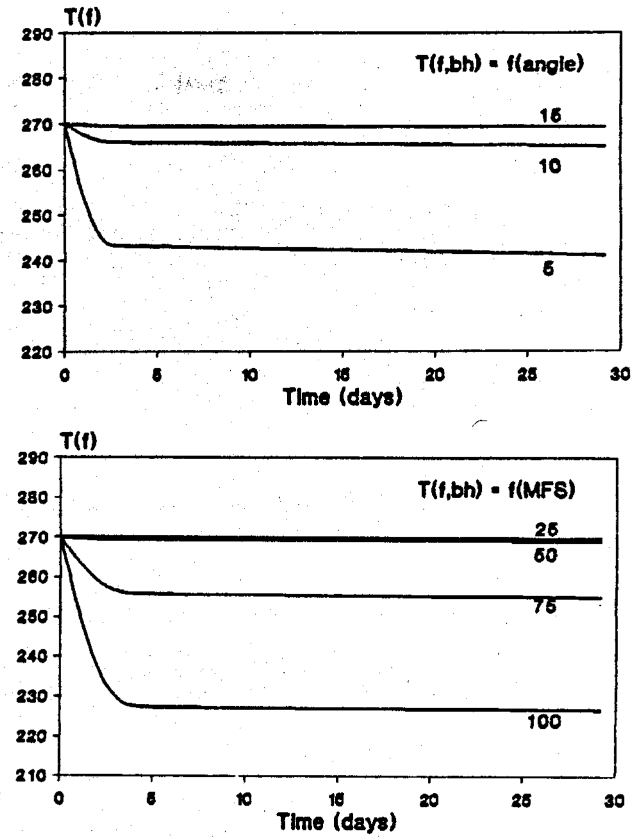

Fig.6 Cooldown curves for Well Pair 011-03 for the tracer-test period as a function of return-flow angle (upper) and mean fracture spacing (lower).

for the thermal front also indicates the possible loss of tracer by thermal degradation or retardation in the tuff formation, especially considering that only 0.5 % of the tracer mass was recovered. The thermal transient time for well 03 for small-angle return flow was about 3-4 days compared to the reported maximum peak value time of 12 days. The rapid thermal cooldown transient to equilibrium between the estimated residence time through the heat-exchanging fractures and the thermal constant of the rock blocks supports the concept of rapid return flow and large-size rock blocks for heat transfer. If the mean temperature of the reservoir is indeed about 270 °C, return-flow reinjection at the periphery of the heat zone would provide the greatest potential for maximum secondary thermal extraction as well as maintain reservoir pressure for the active life of the resource. The total heat extractability would be governed by the volumetric zone of return flow.

Table 3
Tracer-Test Heat-Sweep Cooldown Estimates

Return-Flow Angle (°C)	T(f,bh) at 14 days for Well Pair 011-1	011-03
5	--	242
10	--	266
15	197	269
30	240	270
45	260	270
60	265	270
Mean Fracture Spacing (m)		
25	270	270
50	240	269
75	191	256
100	158	227

This preliminary report of this first tracer experiment shows the type of experimental measurements possible to obtain a clearer picture of the Mutnovsky geothermal prospect. Two improvements are recommended for future tests: (1) increase the mass of the fluorescein tracer by an order of magnitude to increase the measurement precision of the response curves, and (2) if possible, measure the downhole temperatures during the experiment. Another recommendation for a future tracer experiment is to add a second tracer with different potential retardation properties to examine the difference in tracer response.

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