DOUBLET TRACER TESTING IN KLAMATH FALLS, OREGON

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ABSTRACT

A tracer test was carried out in a geothermal doublet system to study the injection behavior of a developed reservoir known to be fractured. The doublet produces about 320 gpm of 160ºF water that is used for space heating and then injected; the wells are spaced 250 ft apart. Tracer breakthrough was observed in 2 hours and 45 minutes in the production well, indicating fracture flow. However, the tracer concentrations were low and indicated porous media flow; the tracers mixed with a reservoir volume much larger than a fracture.

INTRODUCTION

The injection of spent geothermal fluids provides for an environmentally acceptable means of disposal and retards the impact of production on reservoir pressure. However, fluid injection also lowers the enthalpy of production wells so they become useless. What happens in a particular geothermal field is still a matter of speculation. Understanding of geothermal injection is made difficult because the reservoirs are highly fractured and isotropic. There is a need to extend our experience and know-how in geothermal injection technology.

The work reported in this paper was carried out in Klamath Falls, Oregon, in early-mid 1983. It is a progress report on a tracer test that was done as one part of a larger reservoir engineering research project. The main element of this project was an aquifer pump-injection-tracer test carried out in mid-late 1983. The Klamath Falls project had two main objectives: 1) to further our understanding of geothermal injection phenomena, and 2) to provide reservoir engineering data to estimate the effect of pumping on wells with downhole heat exchangers. The doublet tracer test addresses the first of these objectives.

The hydrogeology of the Klamath Falls area and the city's geothermal resources are discussed by Sammel (1980). The current status of hot water use in Klamath Falls is reported by Lund (1982); including institutional issues.

DOUBLET SYSTEMS

The Klamath Falls region is characterized by a network of northwest to southeast faults and fractures. The apparent geothermal resource is 3 - 4 miles long and about one mile wide; along the regional structure. It is a low-to-moderate temperature field and is located on the northeastern side of the city, where basin sediments meet uplifted rocks. The reservoir formation is almost mil to 1500 ft deep and consists of sedimentary deposits and volcanic rocks. The permeable zones of wells tend to be between basalt flows or granular sediments overlain by clay and silt deposits.

The main use of the geothermal resource in Klamath Falls is in space heating. More than 400 wells have been drilled since about 1930. The wells range in depth from 100 - 2000 ft (30 - 600 m) and reach temperatures of 70 - 230ºF (20 - 110ºC). The waters are of good quality with dissolved solids in the range of 800 - 1200 mg/kg. Downhole heat exchangers are used in most of the 400 wells.

Less well known, than the downhole heat exchanger wells, are the doublet systems of Klamath Falls. These systems have one production well and one injection well. The hot water pumped from the production well is used for space heating via heat exchangers and then disposed of by injection. The two wells tend to be of similar depth and design; they are closely spaced. Several wells in the city are pumped, but there is no injection of the spent fluids; the storm drain receives them. Also, some downhole heat exchanger wells are pumped a little to maintain wellbore temperature.

Four doublet systems were identified as candidates for tracer testing: Klamath Union High School, Mazama High School, Mills School and the YMCA Center. The well data for these doublets are shown in Table 1. While these systems are the same in concept and similar in capacity, their operation is different. The main difference is the flowrate. The YMCA doublet is usually turned off during the night and has a low flowrate when in use. The wells

Table 1. Well Data on Doublet Systems in Klamath Falls

	Location							
	Union		Mazama		Mills		YMCA	
Item	P	I	P	I	P	I	P	I
Drilled (yr)	1964	?	?	1966	1961	1957	1979	1978
Depth (ft)	257	240	972	1210	800	809	1410	2016
Casing (ft)	257	120	934	1104	800	809	982	510
Perforated (ft)	176-180 236-257	--	60-400	–	680-800	769-809	--	–
Flow[a] (gpm)	?	?	360[b]	450[c]	250[c]	100[c]	310[b]	300[b]
Temperature[a] (ºF)	?	?	142	136	192	182	147	111
Spacing (ft)	~250		~300		~100		~400	
Pumping[d] (gpm)	~320		?		Low		20-40[e]	
Temperature [f] (ºF)	~160		~140		?		~140	

a) Completion flow test
b) Air lift pumping
c) Artesian flow
d) Current pumping
e) Intermittent flow
f) Production well

in the Mills system are apparently not always pumped because they also have downhole heat exchangers; the wells are quite closely spaced. The Mazama doublet is operated all the time at a reasonable but unknown flowrate. It is located southeast of the city, away from the area of greatest interest.

UNION DOUBLET

The Klamath Union High School doublet system is located where surface manifestations were found before, for example, Big Spring. The high school is close to the County Museum which is the area of main interest in pumping-injection-tracer project. There are many other wells in the same area, some of which are pumped. The use of geothermal water at the high school dates back to 1946. The present double system started operating about twenty years ago.

The production well is 257 ft deep and perforated for 25 ft, most of which is near the bottom. A look at Table 1 shows that the injection well is 240 ft deep and cased to 120 ft; it was drilled at least 10 years earlier than the production well. Th wells are closely spaced, at a distance of about 250 ft. The Union doublet system was selected for this study because of the high flowrate and its location.

When school starts in the fall, the Union doublet system is turned on. It stays on until school is out in the spring. There is a downhole pump in the production well which pumps a constant amount the whole school year. The flow is not measured. However, the pump installer estimates the flowrate to be about 320 gpm, based on the vertical turbine pump specifications, static water level and wellhead pressure. The doublet heating system is shown in Figure 1. At well site, there are two buildings that are heated: a machine shed and a residence. They are heated by a slip stream from the wellhead. The shed system is turned on/off manually when needed and uses 4-5 gpm. The residence system is thermostatically controlled and uses 8-10 gpm when on. The return fluid from both of these systems is piped to the annulus of the production well, 5-6 ft below the wellhead. Therefore, the maximum slip stream flowrate is 15 gpm, or less than 5% of the total pump rate.

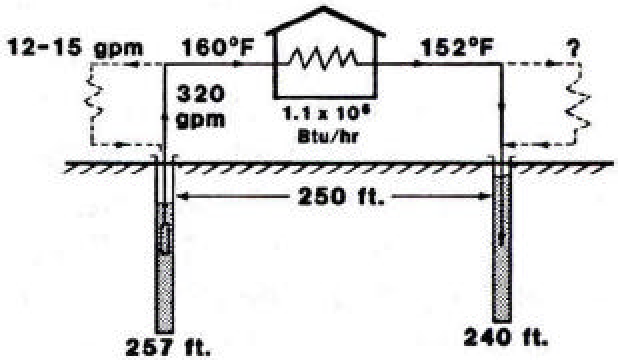

Figure 1. Klamath Union High School doublet and heating system.

The high school is about 600 ft away from the doublet. The hot water goes to the school in a 6-in. pipeline and then passes through 13shell-and-tube heat exchangers which are connected in a mixed series/parallel arrangement. The geothermal water is cooled in the heat exchangers and returned to the injection well. We need to know the travel time of the hot water from the production well to the injection well. This will depend on the flowrate and the volume of the piping and heat exchangers. It takes about 3 minutes for water pumped at 305 gpm to travel 600 ft in a 6-in. pipe. If we assume that each of the 13 heat exchangers has the same volume as 600 ft of pipe, it will take 45 minutes for the geothermal water to go from one wellhead to the other. This is an order of magnitude estimate.

On pumping, the geothermal water cools a few degrees. At the start of the heating season, the water temperature is 165ºF (74ºC), but it cools by 5ºF in 3-10 days, depending on the heat load. Once this initial cooling has occurred, the water temperature remains constant until springtime. The following fall, the temperature is back to 165ºF at startup. It seems likely that the injection of spent fluids causes this cooling of the production water. Long-term cooling of the hot water has been observed by the operators of the Union doublet system. The records are not to be found, but it seems that the temperature dropped 6ºF at about the same time as the Museum well (1235 ft deep) was drilled in 1975; there may or may not be a connection. The geothermal water enters the high school heat exchangers at 160ºF (71ºC) and leaves typically at 152ºF (67ºC). At 305 gpm, this corresponds to 1.1×10^6 Btu/hr or 323 kW of thermal power.

At the site of the injection well, there is a swimming pool. It is heated by the cooled geothermal water returned from the high school building before it is injected. The arrangement is depicted in Figure 1. A slip stream is piped to two shell-and-tube heat exchangers in parallel. The amount of fluid used in the swimming pool exchangers is not known; neither are the discharge temperatures. A reasonable guess would be that the swimming pool's system cooled the injection fluid by a degree or two, and that it added a few minutes to the fluid residence time.

TEST PLANNING

The doublet tracer test was the first part of a larger reservoir engineering study of the Klamath Falls resource. This large study involved the wells of the recently constructed district heating system which has not yet been operated. The production well is located on the northeastern side of the resource about 3000 ft from the Museum well. This great distance and the many unknown factors in geothermal tracer testing called for a small-scale test beforehand: a doublet tracer test.

Iodide has been determined to be a useful chemical tracer for geothermal systems (Horne, 1982). Its background concentration tends to be low and because it is a halide, it is unlikely to interact much with the reservoir formation. Iodide salts are, however, expensive and difficult to analyze in most waters. Fluorescent dyes are commonly used in groundwater tracer studies (Smart and Leidlaw, 1977). They are inexpensive and can easily be analyzed in low concentrations. The dyes used in water tracing are organic chemicals developed for low (ambient) temperature use. They are likely to break down and lose their fluorescent properties at geothermal temperatures. The nature of extent of this loss are, however, unknown; they are of no interest in common water tracing.

Rhodamine WT and fluorescein dyes were selected for use in the doublet tracer test. It was also decided to try potassium iodide because of its potential use in high-temperature systems (at the time the authors were in the planning stge of a large high-temperature reservoir tracer test elsewhere and wanted to try the chemical, and that analytical method). The dyes are best measured in a fluorometer which is simple to use and inexpensive. To measure the iodide, an ion specific electrode was used (Jackson, 1983). The advantage of both methods (fluorometer and electrode) is that they are easily carried out in the field. The following detection limits were thought to apply for these techniques and materials:

Rhodamine WT	0.013 ug/kg
Fluorescein	0.029 ug/kg
Potassium iodide	1.0 mg/kg

The literature was searched for data on possible health risks associated with the tracer materials. It was found that no ill effects would be likely to occur upon drinking the geothermal water during the tracer test.

Two cases that represent the likely extremes were considered when estimating the mass of tracer materials to be injected: radial and doublet flow. When a fluid injected into one well moves radially, the breakthrough time t_r at distance r is given by the expression:

$$t_r = \frac{pr^2fh}{Q}$$

where ϕ and h are the reservoir porosity and thickness, respectively, and Q the flowrate. The porosity-thickness product ϕh can be replaced by δ to represent the flow in a planer fracture of that thickness. A doublet configuration acts as a source-sink system. If x is the doublet spacing, the breakthrough time t_x will be 1/3 that of a radial system (Gove, et al., 1970 and Klett, et al., 1981), namely:

$$t_x = \frac{px^2fh}{3Q}$$

We assume that the tracer material mimes uniformly with all the fluid injected into the reservoir. Its concentration at the production well will then be the total mass of tracer divided by the fluid volume injected until breakthrough. The following data were used in the calculation:

Spacing	250 ft
Thickness	25 ft
Porosity	10 %
(Flowrate 305 gpm)	

The corresponding radial and doublet volumes (V=Qt) were 13,800 m^3 and 4,600 m^3. If the desired tracer concentrations in the production well were empirically set 100x and 20x the detection limits of the dyes and potassium iodide, respectively, then the following shows the mass of tracer needed and the estimated breakthrough times:

	Radial	**Doublet**
Rhodamine WT	18 g	6 g
Fluorescein	400 g	133 g
Potassium iodide	276 kg	92 kg
Breakthrough time	100 hr	67 hr

Permits were obtained from the Department of Environmental Quality (State of Oregon) and the Department of Health Services (Klamath County) to inject 90 g and 900 g of rhodamine WT and fluorescein, respectively, and 690 kg of potassium iodide (much less was injected). The price of the three tracers was similar on a pound-mass basis; 8-9 $/lb.

FIELD WORK

The rhodamine WT and fluorescein were mixed in 100 gallons of geothermal water. It took 15 minutes to pump this water into the injection well. One pound (450 g) of each material was injected. The rhodamine WT was in the form of a liquid 20% active; the one pound solution contained 90 g of this red-pink dye. Fluorescein comes in dry powder form and is greenish in water. All of this material was considered active. The potassium iodide was mixed in 150 gallons of geothermal water; it is readily soluble and colorless. The amount used was 500 lb (227 kg). It took 20 minutes to inject this solution. An ordinary agricultural sprayer was used for the injection. The tracers were injected at the wellhead of the injection well. The wellhead piping is such that the dyes are mixed immediately with the down-flowing water. For the amounts of tracers injected (shown), the expected concentrations at the production well were:

	Radial	**Doublet**
Rhodamine WT (90 g)	0.0065 mg/kg	0.020 mg/kg
Fluorescein (450 g)	0.033 mg/kg	0.10 mg/kg
Potassium iodide (227 kg)	16.0 mg/kg	48.0 mg/kg

An automatic sampling apparatus was set up at the production well. It consisted of sixteen three-way solenoid valves that were operated by a programmable timer. The apparatus takes fifteen samples of any volume at any interval. The fluid to be sampled is directed through a filter and then cooled in a coil of tube. Flow is continuous through the apparatus until one of the three-way valves is activated by the timer. The flow is then directed into a sample bottle for a predetermined time. The apparatus was programmed to fill one bottle every ½ hour. Five other wells were sampled by hand during the tracer test. At first, samples were collected every hour, then less frequently. The wells sampled are shown in Figure 2: Balsiger (260 ft deep), Creamery (765 ft), Eccles (787 ft) and Garrison (240 ft). The flowrate of the Balsiger well was measured 75 gpm and the temperature 180°F. The flow in other wells had to be guessed; Balsiger 30 gpm, Eccles and Friesen 20 gpm, and Garrison 10 gpm. Other wells in the area were not pumped at the time of the testing.

The dyes were measured in a Turner 112 fluorometer. One of the purposes of the tracer test was to evaluate which of the two dyes was better for geothermal tracer studies. We found out that injecting them at the same time was not desirable. A mixture of two dyes tends to have less color than just one dye. And although recommended, lamps and filters were used in the fluorometer, there was measurable interference. A reading on the fluorometer could not be assigned to one dye only; the values obtained were, therefore, qualitative. During the tracer test, the water samples were analyzed the same or following day that they were collected, at least for the first week or so. The fluorometer was set (lamp and filters) to detect fluorescein. Not every sample collected was analyzed, but every second or third. We wanted to know where and when the tracers broke through. The idea was that we could later analyze the samples initially left out. However, a complicating factor is that the color of dye solutions decreases with time, more rapidly so for fluorescein than rhodamine Wt. The samples from one well were measured with the rhodamine WT setting of the fluorometer. The iodide was measured by ion-selective analysis; the Accment 750 meter from Fischer was used.

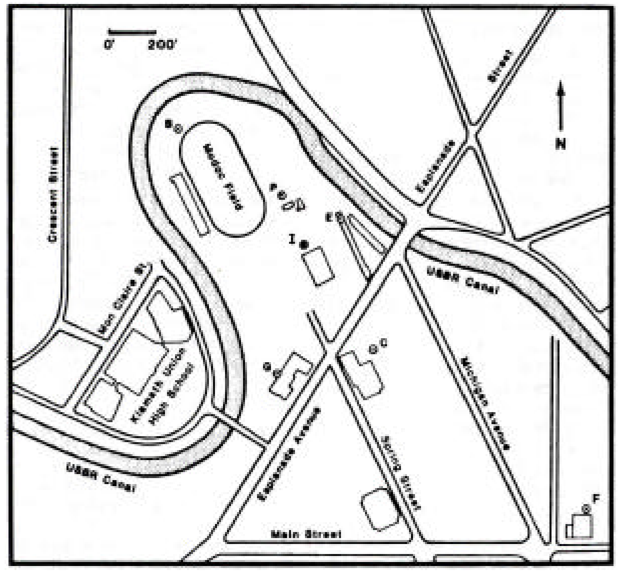

Figure 2. Location of wells in doublet tracer test: (I) Injection, (P) Production, (B) Balsiger, (C) Creamery, (E) Eccles, (F) Friesen and (G) Garrison.

BREAKTHROUGH CURVES

A tracer breakthrough curve shows the concentration of a tracer with time; a sort of a travel log. It provides a record of what happens underground when a fluid flows between the wells of a doublet system, for example. The interpretation of a tracer breakthrough curve depends on knowing what physical and chemical principles apply. In geothermal reservoirs, these principles are little known and field data are limited. The doublet tracer test was carried out to address this problem.

The flow pattern in the Klamath Union High School doublet is complicated by the fact that other pumped wells are in the area. The largest of these is the Creamery well about 450 ft away from the injection well and pumped 75 gpm. These and other wells are shown in Figure 2. The following breakthrough times were measured in the wells:

Production	2-3/4 hr
Creamery	20hr
Balsiger	~100 hr

These times are only a fraction of what was expected. The tracer broke through in the production well 25-75 times faster than estimated (above) before the test. Tracer returns were not detected in the Friesen and Garrison wells.

Breakthrough curves for the production and Creamery wells are shown in Figures 3, 4 and 5. Other data are not reported here for brevity. Figures 3 and 5 show the fluorometer reading (not calibrated) when set for fluorescein and rhodamine WT, respectively. The concentration readings are not comparable. In Figure 5, there are two data sets; the lower values were measured about two months later. Figure 4 shows the concentration of potassium iodide in the production well.

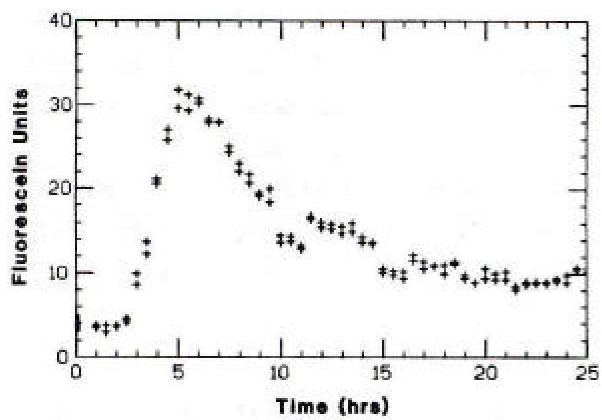

Figure 3. Fluorescein breakthrough curve in production well.

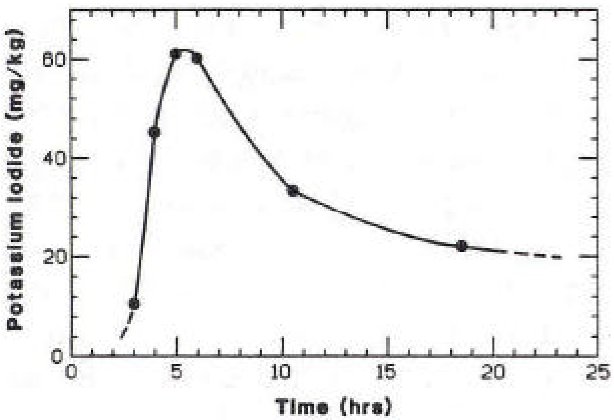

Figure 4. **Potassium iodide breakthrough curve in production well.**

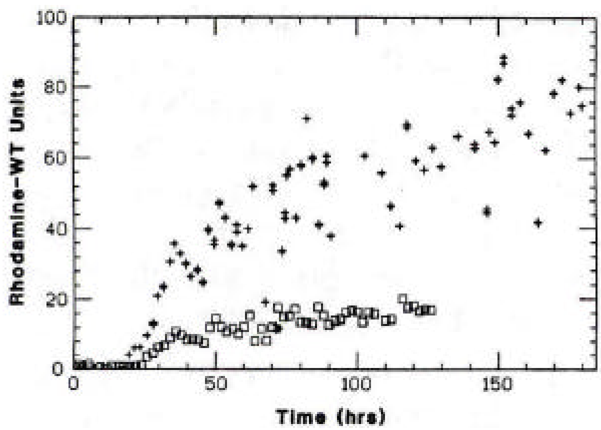

Figure 5. **Rhodamine-WT breakthrough curve(s) in Creamery well. Samples measured during test (+) and two months later (~).**

The potassium iodide concentration expected in the production well was 16-18 mg/kg; the maximum observed was about 60 mg/kg. An examination of Figure 4, and keeping in mind the circulation time, shows that the first breakthrough was similar to a doublet behavior. Also, the potassium iodide concentration falls to a level of about 20 mg/kg in a day or so. This would say that with time the system approaches radial behavior. These observations are based on radial and doublet fluid volumes of 13,600 m^3 and 4,600 m^3, respectively.

However, the fluid volume injected until breakthrough in the production well was small. In 2-3/4 hr at 305 gpm, only 191 m^3 o water was injected. The doublet and radial volumes that give appropriate tracer concentration (shown above) are 24 and 72 times larger! What is the cause of this order-of-magnitude discrepancy? In water-flooding (Craig, 1971), the "area sweep efficiency at breakthrough" for common well patterns is usually 50-80%. This means that the area (volume) swept by injected water is typically of the same order-of-magnitude as the pattern drainage area. In geothermal, we have more than simple displacement.

The doublet system at the high school has been in operation more than 20 years. For about nine months each year, 305 gpm are pumped out at 160ºF and injected at about 152ºF. It is clear that the reservoir rock between the production and injection wells cannot sustain the thermal output of the system. There is likely to be intensive mixing of the injected and hotter fluids in the drainage volume of the production well; the cooled fluids tend to flow down and hotter fluids ascend. This mixing action must be rapid as evident from the experimental results. The following working hypothesis seems to fit the observations: the injected fluid moves rapidly along fractures to the production well, and on the way, some of it mixes with fluids flowing up/down in cross-flow fractures.

CONCLUDING REMARKS

The results presented in this paper are one part of a larger project. The data have not been fully analyzed, so the outcome of the doublet tracer test reported here must be viewed as a progress report. Nevertheless, some conclusions are warranted from the observations made so far:

1. The automatic sampling apparatus worked well and is a time saving device of great value. The two analytical methods, used to measure the halide ion and dyes concentrations, were found to be most applicable in the field. Better methods are available for measuring iodide in the laboratory, but fluormetry is best for dyes. More time and care was needed for the analytical techniques used than anticipated.

2. Dyes are more cost effective than halides for tracer work in low-to-moderate temperature geothermal reservoirs.

3. Rapid tracer breakthroughs were found in wells that were pumped a high rates. These also happen to lie parallel to the dominant fracture/fault direction northwest to southeast of the region.

4. A great disparity was found between reservoir characterization based on tracer concentration and breakthrough times. The concentrations

measured indicate doublet behavior initially, and radial behavior at later times. The tracer breakthrough times were rapid and indicated much lower porosity-thickness values than expected.

5. The data point to an important consequence for geothermal injection. While tracer returns (breakthrough time) indicate small reservoir volumes, the mixing or contact volume of the fluid appears to be much larger. The consequences of injecting cold fluids would appear not to be as great as indicated by tracer tests.

ACKNOWLEDGMENTS

We would like to thank our colleagues at the U.S. Geological Survey and Lawrence Berkeley Laboratory for their cooperation in this work. Our appreciation to the people of Klamath Falls, in particular, Earl Ferguson, superintendent, for his permission in carrying out the test. The following students at Stanford University also took part in this project: Gardner Walkup, Clair Jensen and John Gilardi. We want to thank the several students at Oregon Institute of Technology that helped in the sample taking and analysis. Thanks to Marty Molloy and Jane Hadley of U.S. Department of Energy for their contribution to this project. This work was carried out under the auspices of the Stanford Geothermal Program and the Geo-Heat Center with support from the U.S. Department of Energy.

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