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TRACER TESTING AT STEAMBOAT HILLS, NEVADA, USING FLUORESCEIN AND 1,5-NAPHTHALENE DISULFONATE

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ABSTRACT

A tracer test was recently initiated at the Steamboat Hills, Nevada, geothermal system in order to test the performance of the candidate tracer 1,5-naphthalene disulfonate and to evaluate the flow patterns of fluids entering the reservoir through a recently drilled slim hole injector. The tracer fluorescein was used as a companion dye to 1,5-naphthalene disulfonate. Early returns indicate comparable performance for the two tracers with both appearing to behave conservatively. The Arrhenius first-order thermal decay rate of 1,5-naphthalene disulfonate was determined over the temperature range of 310-330 ^{o}C using a batch autoclave reactor under conditions that simulate a hydrothermal environment. The tracer was found to be remarkably stable with only 20% decay measured after one week in the autoclave at 330^{o}C. The long linear tailing portion of return curves from a tracer test initiated in 1992 indicates the effective fluid volume at Steamboat Hills to be on the order of 30 million m^3 (8 billion gal). The natural recharge rate was estimated to be about 300 kg/sec (5000 gal/min).

INTRODUCTION

The Far West Capital (FWC) Steamboat Hills geothermal field is located approximately 14km (9 miles) south of Reno, Nevada. Figure 1 shows the location of the Steamboat Hills geothermal field in northwest Nevada.

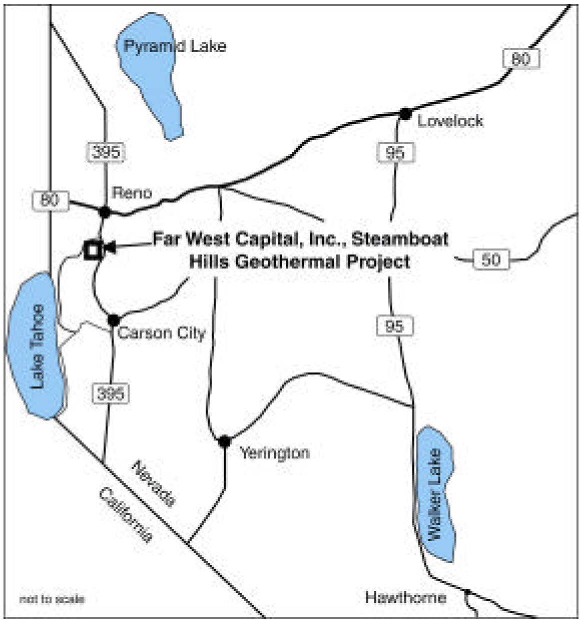

Figure 1. Location of the Far West Capital Steamboat Hills geothermal project.

Figure 2 shows the location of production, injection and exploratory slim holes drilled on the FWC Steamboat Hills geothermal operations area. Average geothermal fluid production temperature is approximately 160°C (320°F). Geothermal production operations began in 1986 with the SB 1 power plant. The SB 1 power plant was modified in 1989 and renamed SB 1/1A). It supplies

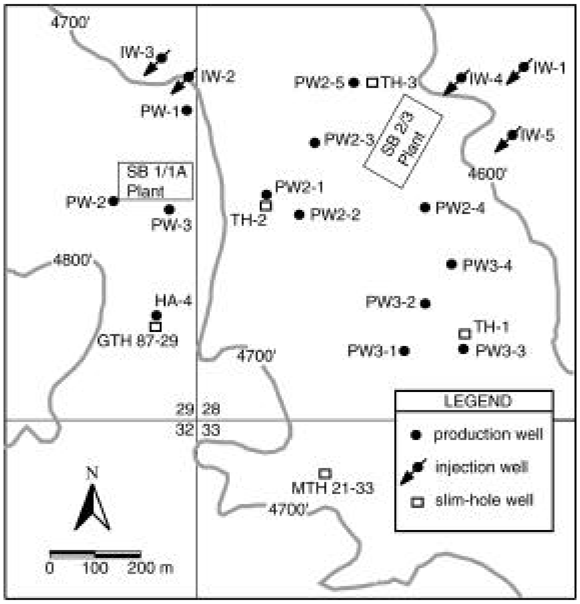

Figure 2. Location of production, injection, slim hole exploration wells and power plants at the FWC geothermal operations area.

7 MW of electrical power with production of 230 kg/s (4,000 gal/min) of geothermal fluid from three production wells (PW-1, PW-2 and PW–3). Spent brine injection for the SB 1/1A is through injection wells IW-2 and IW-3. The majority of the spent fluid from SB 1/1A is injected into well IW–3.

Geothermal power production output was increased in 1992 with the addition of the SB 2/3 power plant. The SB 2/3 plant produces 24 MW of net electrical power. Geothermal fluids are produced from nine production wells (PW2-1 through PW2-5 and PW3-1 through PW3-4). These nine wells supply 1,140 kg/s (20,000 gal/min) of geothermal fluid to the SB 2/3 power plant. Spent geothermal brine is injected into the three wells IW-1, IW-4 and IW-5. IW-5 is the largest of these injectors, accepting approximately one-half of the spent fluid from the SB 2/3 power plant operations.

Two tracer tests have been carried out at the Steamboat Hills field. The first tracer test was initiated in 1992. In that test, a combination of fluorescein and rhodamine WT was pumped into well IW-4 and monitored at selected producers over the subsequent 5.6 years.

In the second test, a combination of fluorescein and 1,5–naphthalene disulfonate was injected into the geothermal reservoir via slim hole GTH 87–29 (see Figure 2 for well and slim hole locations). The objective of the test was to compare the performance of 1,5–naphthalene disulfonate to that of the tracer fluorescein and to determine the flow patterns of fluids injected into deeper portions of the Steamboat Hills geothermal system. An additional objective of this project was to determine the decay kinetics of 1,5–naphthalene disulfonate.

SUBSURFACE GEOLOGIC CONDITONS AND WELL COMPLETIONS AT STEAMBOAT HILLS

Subsurface geologic conditions at Steamboat Hills consist of a thin layer of alluvium and geothermal sinter deposits. Volcanics and fractured granodiorite lie beneath the alluvium and sinter deposits. The volcanic sequence thickness varies through the field from 0 to 240 m (775 ft). However, most of the production wells are drilled through approximately 100 m (300 ft) of volcanics.

Fractured granodiorite underlies the volcanic sequence and comprises the geothermal reservoir system at Steamboat Hills. The permeability of the fractured granodiorite is essentially infinite. The total thickness of the granodiorite is unknown. The deepest hole drilled in the area (GTH 87–29) encountered granodiorite to a depth of 1,220m (4,000 feet).

Typical production well completions in the area consist of setting 35-cm (13 3/8") production casing to a depth of 180 m (600 feet). The production wells are then completed with a 31-cm diameter open-hole to depths of 300 m (1000 ft) (see Figure 3).

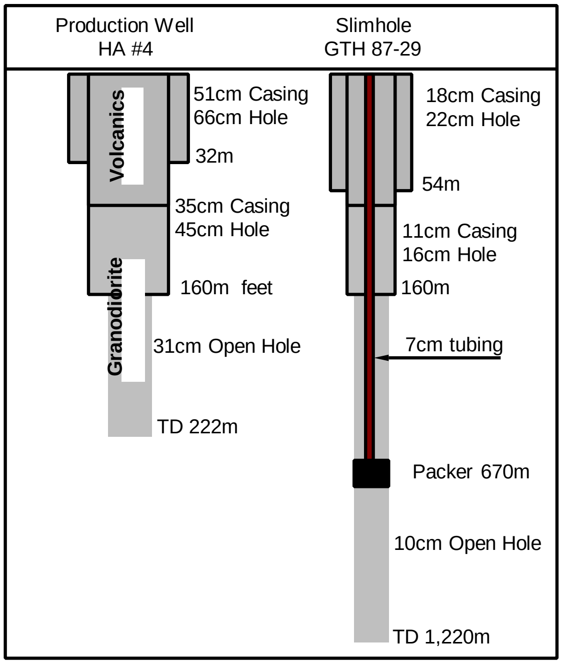

Figure 3. Completion of tracer injection slim hole GTH 87-29 and typical production well (HA-4) at Steamboat Hills

Injection wells IW-1, IW-2, and IW-4 are completed to depths of 760m (2,500 feet). Injection wells IW-3 and IW-5 have shallow completions of approximately 330m (1,080 feet).

PREVIOUS TRACER TEST

A tracer test was initiated at Steamboat Hills in December, 1992 (Rose and Adams, 1994). In that test, 114 kg (250 lb) of rhodamine WT was co-injected with 91 kg (200 lb) of fluorescein into injection well IW-4. Shown in Figure 4 are plots of return curves for the nine production wells monitored during the subsequent 5.6 years. It is evident that with the very rapid return of injected fluids to the production wells an injected solute would be quickly mixed throughout the reservoir. And, since all of the produced fluids at Steamboat Hills are reinjected, the fluorescein concentrations at the nine producers eventually converge as the tracer is thoroughly mixed throughout the reservoir.

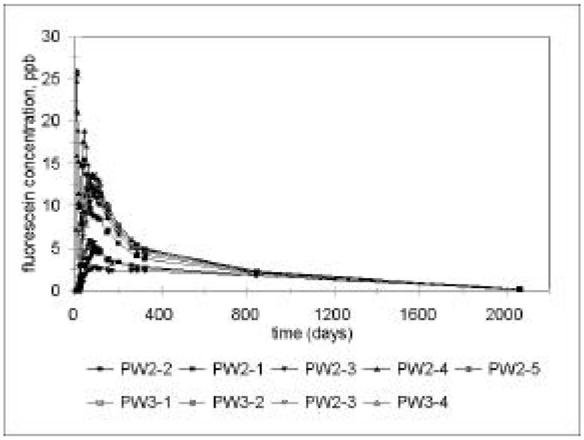

Figure 4. Fluorescein return curves from the tracer test initiated in December, 1992, at Steamboat Hills.

It was observed that the long tailing portions of the return curves shown in Figure 4 attain a fairly linear decline rate after about 800 days. Fluorescein has been shown not to adsorb on reservoir rock under geothermal conditions. In addition, the fluid temperatures at Steamboat Hills are below that which would cause any measurable thermal decay of fluorescein over the duration of the test (Adams and Davis, 1991). We conclude therefore that the linear decline in fluorescein concentration results principally from the mass transport mechanisms of advection and diffusion.

The Steamboat Hills “reservoir” is similar to many other geothermal reservoirs in that the areal and volumetric extent of the system is poorly defined. No distinct boundary can be drawn between reservoir and non-reservoir. It is reasonable to assume, however, that there exists a region of brine-filled fractures wherein the flow processes are controlled to a large extent by the induced flow paths between the injection and production wells and to a lesser extent by naturally occurring convective processes. For the purposes of this discussion, this actively convective region is referred to as the reservoir.

The reservoir is surrounded by domains that are largely unaffected by the induced flow processes within the producing geothermal system. Such regions could consist of relatively stagnant zones or of zones that are dominated by natural convection. Therefore, if a conservative tracer is introduced into the reservoir via injection wells, it will be mixed throughout the system largely by induced convective flows between the injectors and producers. In addition, it will be advected out of the reservoir by aquifer cross-flow or diffuse into relatively stagnant regions (vugs, pores, and dead-end fractures) within and adjacent to the reservoir.

Rose and coworkers (1997) showed that the linear tailing portion of the return curves of conservative tracers can be used to estimate both the effective reservoir fluid volume and the rate of reservoir recharge by surrounding aquifers. Using this approach, the effective reservoir volume was calculated to be approximately 30 million m^3 (8 billion gal); the natural recharge rate was calculated to be approximately 300 kg/sec (5000 gal/min).

DECAY KINETICS OF 1,5-NAPHTHALENE DISULFONATE

The decay kinetics of 1,5-naphthalene disulfonate was determined under controlled laboratory conditions using autoclave batch reactors. The experimental approach is described elsewhere (Rose *et al.*, 1998).

The thermal decay of 1,5-naphthalene disulfonate can be modeled by the first-order differential equation:

$$-\,dC_n / dt = k_n \cdot C_n \qquad (1)$$

where C_n is the concentration of 1,5-naphthalene disulfonate and k_n is the first-order rate constant. Solution of this equation results in the following relationship between C_n and t:

$$\ln\left(\frac{C_n}{C_n^0}\right) = -k_n \cdot t \qquad (2)$$

where C^0_n is the initial concentration of 1,5-naphthalene disulfonate. The temperature dependence of k_n can be described by the Arrhenius relationship:

$$k_n = Ae^{(-E_a/RT)} \qquad (3)$$

where A is the pre-exponential factor, E_a is the energy of activation, R is the gas constant and T is absolute temperature. A linearization of the Arrhenius expression results in the following:

$$\ln k_n = \ln A - \frac{E_a}{RT} \qquad (4)$$

Figure 5 shows a fairly linear relationship between ln k_n and inverse temperature, indicating that the Arrhenius equation provides a reasonable means for expressing the temperature dependence of the decay rate constant.

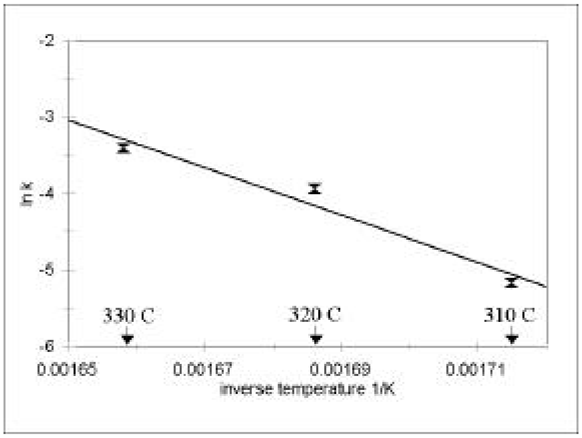

Figure 5. Arrhenius plot of the decay rate constant for 1,5-naphthalene disulfonate under laboratory conditions. The vertical dimension of the data point marker approximates the uncertainty in ln(k).

The straight line in Figure 5 was determined by a linear least-squares fit to the data. Solving for the slope and intercept results in the following expression that can be used to determine the decay constant at any temperature between 310°C and 330°C:

$$\ln k_n = 48.2 - \frac{31100}{T} \qquad (5)$$

CURRENT TRACER TEST

On July 24, 1998, 91 kg (200 lb) of uranine (sodium salt of fluorescein) was mixed with 100 kg (220 lb) of the disodium salt of 1,5-naphthalene disulfonic acid (1,5-nds) in a tank with approximately 3.8 m^3 (1000 gal) of water. Upon dissolution of the tracers, the solution was injected over a period of approximately 45 minutes into slim hole GTH 87–29. Brine was then injected continuously into GTH 87-29 at a rate of 9 kg/sec (140 gal/min).

Fluids from the production wells were sampled periodically during the subsequent several months for analysis at the EGI tracer development laboratory in Salt Lake City. Fluorescein was analyzed by spectrofluorometry using a Perkin Elmer LS-30 luminescence spectrometer. 1,5-nds was analyzed by High Performance Liquid Chromatography (HPLC) in combination with spectrofluorometric detection using a Hypersil Hypurtiy Elite C18 column (5 μ, 150 x 4.6 mm). The mobile phase consisted of a pH 7.5, phosphate-buffered, 5 mM solution of tetrabutyl ammonium phosphate in methanol and water.

Shown in figures 6 and 7 are the fluorescein and 1,5-naphthalene disulfonate return curves, respectively, for the 1998 test. It is evident that the two tracers behaved similarly, with respective first arrivals at the production wells appearing at approximately the same time. The initial fluorescein concentrations were approximately 200 ppt, due to residual tracer from the 1992 test.

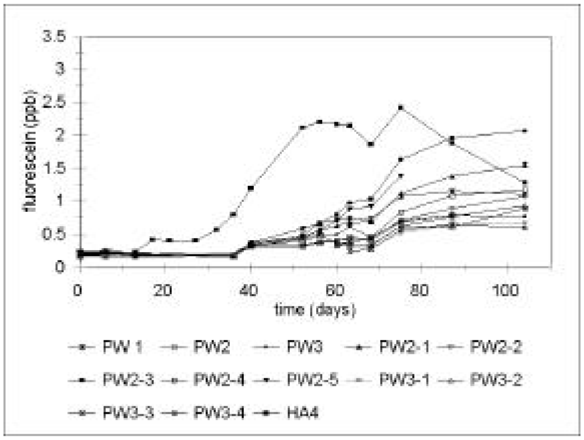

Figure 6. Fluorescein return curves for production wells monitored during the 1998 tracer test at Steamboat Hills.

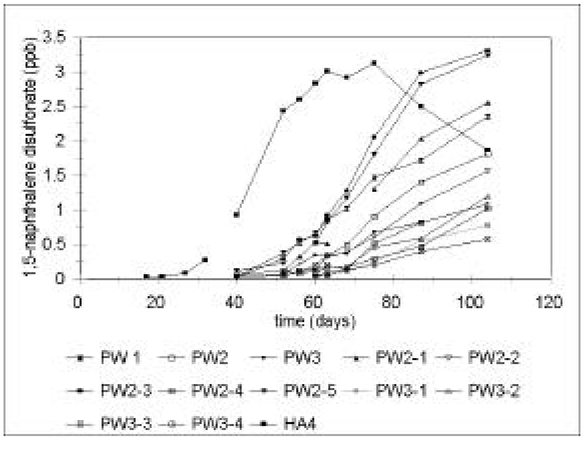

Figure 7. 1,5-naphthalene disulfonate return curves for production wells monitored during the 1998 tracer test at Steamboat Hills.

The strongest return is to well HA-4, which is located 10 m (30 ft) from the tagged slim hole GTH 87-29. As shown in Figure 3, HA-4 has a total depth of only 220 m (720 ft), whereas the slim hole injection well is completed in a deeper region of the reservoir below a depth of about 670 m (2040 ft).

The next strongest returns are to the relatively shallow producers in section 2: PW2-1, PW2-3, and PW2-5 followed by the producers PW1 and PW2. It is believed that the tracer that reached these wells did not travel directly in the subsurface from GTH 87-29, but was produced after having been reinjected via injection wells IW-1, IW-4 and IW-5. The weakest returns were to the deeper wells in section 2 (PW2-2 and PW 2-4), the wells in section 3 (PW3-1, PW3-2, PW3-3, and PW3-4), and well PW-3.

The observed variations between the return curves for the various producers results from several factors. These factors include differences in completion depths between the injection and production wells, the proximity of the production wells to the injection wells, the location of the system's natural recharge, and the location of the wells with respect to fracture orientations within the reservoir system. An analysis of the effect of these factors on the tracer return curves is beyond the scope of this paper.

By comparing the individual return curves for each well for fluorescein and 1,5-naphthalene disulfonate in figures 6 and 7, it is evident that 1,5-naphthalene disulfonate was produced in higher concentration than was fluorescein. Part of this difference is explained by the fact that more 1,5-naphthalene disulfonate was injected than fluorescein.

Figure 8 shows the normalized fluorescein and 1,5-naphthalene disulfonate return curves for production well HA-4. Each return curve has been normalized for the quantity of tracer injected, and the fluorescein plot has been corrected for the initial background concentration of approximately 200 ppt.

It is evident that the two normalized return curves do not overlie each other exactly, as would have been expected for two conservative tracers injected simultaneously. The peak maxima coincide, however, indicating no adsorption by either tracer. Since each curve in Figure 8 is normalized for the nominal mass of each tracer injected, an error in the actual quantity injected of either tracer could have produced the difference in peak heights. The actual injected quantity of each tracer was not measured; only the suppliers' nominal quantities were recorded.

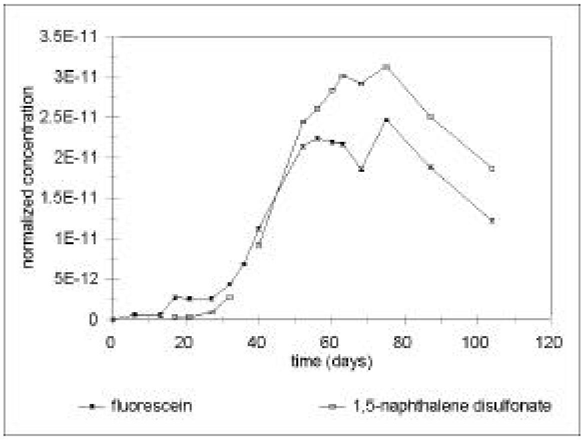

Figure 8. Fluorescein and 1,5-naphthalene disulfonate return curves, normalized to the total injected mass of each. The fluorescein curve was also corrected for the initial concentration present in the reservoir.

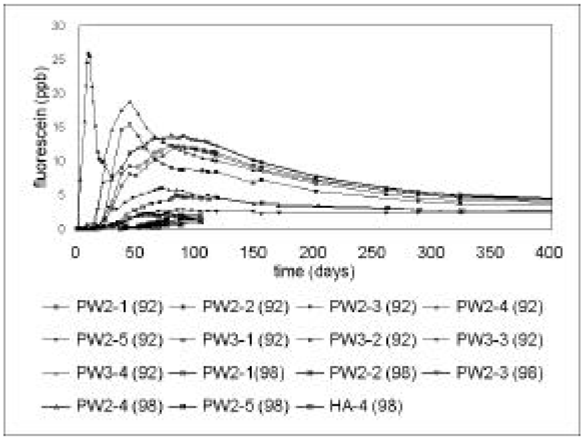

Figure 9. Fluorescein return curves to selected wells from the 1992 and 1998 tracer tests at Steamboat Hills. The thin lines represent return for the 1992 test and the heavy lines indicate return for the 1998 test.

DISCUSSION

The fluorescein return curve data from the 1992 and 1998 tracer tests are plotted in Figure 9. Although the mass of tracer injected was the same in both tests, the return curves have very different shapes, reflecting very different flow patterns. In the 1992 test, fluorescein was injected into IW-4, which flows at approximately 360 kg/sec (5700 gal/min). The first arrival of tracer was observed within a few hours at production well PW2-4 and within a few days at production well PW2-2.

In the 1998 test, however, the tracers were injected into a relatively stagnant section of the reservoir into an injector flowing at a rate of only 9 kg/sec (140 gal/min). As a consequence, the first arrival of tracer was observed at approximately 30 days, with tracer concentrations building very gradually. The difference between the two tracer tests reflects, partially, the difference between injecting into a hydrodynamically active region versus a relatively stagnant region within the reservoir. However, differences in the injection strategy between the 1992 and 1998 also contribute to the differences between the return curves for the two tests. During the 1992 test, the injection rate was equally divided between the three injectors IW-1, IW-4, and IW-5. The current injection strategy allows for a fluid distribution of 20%, 25%, and 55% into IW-1, IW-4, and IW-5, respectively. Also, since the 1992 tracer test, injection well IW-4 was re-completed with casing set to a total depth of 470 m (1540 ft). The well had been originally cased to a depth of 240 m (780 ft). This re-completion was done to reduce injection into the shallow reservoir.

If the decay kinetics of various tracers are known, a convenient method for comparing their performance is by plotting tracer half-lives as functions of temperature, as shown in Figure 10. The curves in this figure have approximately the same shape, although they are offset from each other by several tens of degrees.

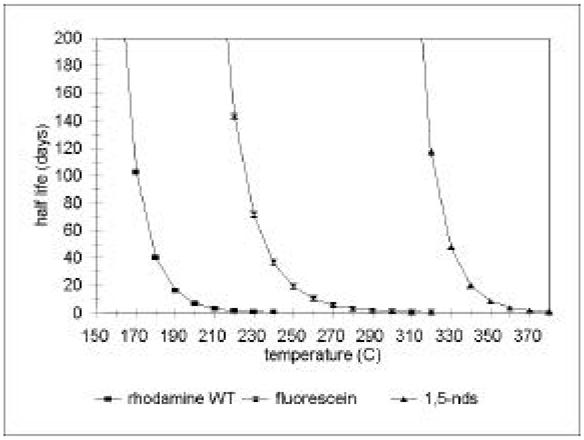

Figure 10. The half-lives of the tracers rhodamine WT, fluorescein, and 1,5-naphthalene disulfonate plotted as functions of temperature.

These plots can also be used to determine an approximate maximum use temperature for each tracer. It is evident that as the temperature is increased there is a region where each curve begins to approach the ordinate asymptotically. In such temperature regions, the half-lives are so short as to render the tracer unusable. Depending on the expected residence times and the quantity injected, however, a relatively short half-life can be tolerated. At the Dixie Valley, Nevada, geothermal reservoir, where the production fluid temperatures measure 250^{o}C, fluorescein was observed in production wells one year after injecting a 91-kg slug (Rose *et al.*, 1998). From the fluorescein plot in Figure 10, it can be seen that at 250^{o}C the half-life is only 20 days. By using the performance of fluorescein at Dixie Valley as a guide and assuming a half-life of approximately 20 days, it is evident that rhodamine WT can be used in reservoirs with production temperatures approaching 185^{o}C, fluorescein in 250^{o}C reservoirs, and 1,5-naphthalene disulfonate in reservoirs as hot as 340^{o}C.

CONCLUSIONS

The fluorescent compound 1,5-naphthalene disulfonate was evaluated in the laboratory and in the field for application as a hydrothermal tracer. The Arrhenius thermal decay rate constant for 1,5-naphthalene disulfonate was determined over the temperature range of 310-330 ^{o}C using a batch autoclave reactor under conditions that simulate a hydrothermal environment. Laboratory data indicate that 1,5-naphthalene disulfonate can be used in reservoirs at temperatures approaching 340 ^{o}C. In a field test at the Steamboat Hills geothermal reservoir, 1,5-naphthalene disulfonate performed comparably to fluorescein, showing no adsorption.

An analysis of the long tailing portion of the return curve from a previous tracer test at Steamboat Hills revealed the effective reservoir fluid volume to be approximately 30 million m^3 (8 billion gal). In addition, the natural recharge rate was calculated to be approximately 300 kg/sec (5000 gal/min).

The two tracer tests contrast the effect on residence time of injecting into either hydrodynamically active or relatively stagnant regions of the reservoir. In the first test, tracer was injected into a high-flow injector and the first arrival of tracer was observed within a few hours. In the second test, tracer was injected into a relatively stagnant region of the reservoir via a slim hole injector and the first arrival of tracer was observed approximately 25 days after injection.

ACKNOWLEDGEMENTS

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