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Tracer Tests Using Naphthalene Di-Sulfonates in Mindanao Geothermal Production Field, Philippines

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ABSTRACT

Complete injection of hot brine from separators has been practiced in Mindanao Geothermal Production Field (MGPF) since 1997. About 200 kg/s of brine is injected into Matingao (MT) re-injection wells and more than 150 kg/s of brine is injected into Kullay (KL) re-injection wells both located at the outflow area of the geothermal system. As early as middle of 1998, significant increase in chloride and other chemical components have been noted in discharge fluids of production wells close to the injection sectors. To establish fluid breakthrough in the production area from the re-injection wells, tracer tests using naphthalene di-sulphonates (NDS) were conducted. Four hundred kilograms of 1,6-NDS and 400 kilograms of 2,6-NDS were injected into wells MT2RD and KL1RD respectively. Well SK2D, the steam producer nearest to MT2RD in terms of bottom hole distance showed significant RI fluid breakthrough. Tracer returns in SK2D are about 20% based on simple one-dimensional flow-channel tracer transport model calculations. Production temperature predicted from cooling model of the well is matched with historical data and showed good conformity.

1. INTRODUCTION

One of the principal environmental constraints imposed on Mindanao Geothermal Production Field (MGPF) (Figure 1) by its Environmental Compliance Certificate (ECC) is to operate the geothermal field at zero disposals. This means that none of the geothermal-related effluents should be disposed of at the surface water streams. Re-injection of brine from the separator stations, disposal sumps and cold cooling tower blow-down of the two power plants is imperative.

Considering the proximity of the Matingao reinjection sector to the Marbel production sector (Figure 2), re-injection returns give rise to a potential problem in the reservoir management of the field as soon as commercial exploitation progressed. Geologic investigations by Pioquinto et al (1997) showed that several structural passageways connect Matingao re-injection and Marbel production sectors. Chemical changes were observed in three Marbel wells by December 1997 namely, APO1D, APO3D and SP4D, and were attributed to reinjection returns. To test if the injected fluids emanated from Matingao re-injection sector, two tracer tests, using sodium flourescein dye in March 1998 and Iodine-131 in December 1998, were conducted in MT2RD. Both test were inconclusive with respect to re-injection returns (Delfin et al., 1999). The inconclusive results were attributed to insufficient tracer mass and possible thermal decay in the case of sodium fluorescein and very short half-life in the case of Iodine-131. Later assessments on the chloride trend with time of wells possibly affected by re-injection returns showed that breakthrough time could be as long as six months.

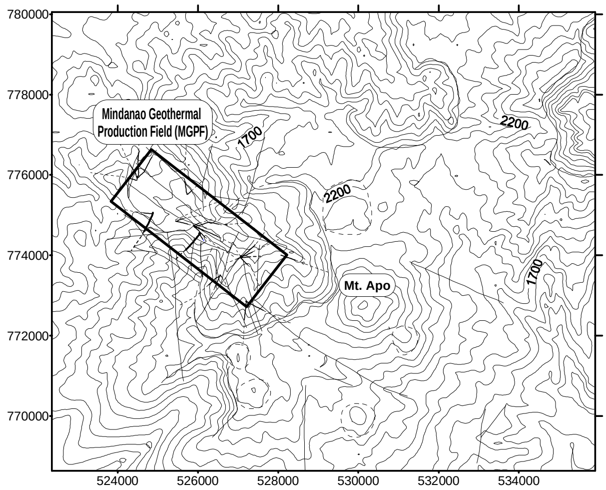

Figure 1. Map above shows the location of Mindanao Geothermal Production Field (MGPF). Also shown are the locations of injection well MT2RD and production well SK2D. Black lines indicate important geologic features.

Naphthalene di-sulphonates were chosen as tracer for the subsequent tracer test in MGPF because of its low detection level (<1 ppb) and its stability at very high temperatures (>300°C) (Rose, et al, 2002). In February 25, 2003, four hundred kilograms of 1,6 naphthalene di-sulphonate (1,6 NDS) was injected into MT2RD. A second tracer using 400 kilograms of 2,6-NDS was injected into KL1RD on March 8, 2003. All production wells discharging were regularly sampled for tracer returns since start of injection.

This paper presents the preliminary assessment on the 1, 6-NDS-tracer breakthrough in well SK2D.

2. METHODOLOGY

Four hundred kilograms of 1,6 NDS was injected into well MT2RD in February 25, 2003. The tracer was dissolved in about 5,000 liters of water and injected into the well using 4TUT pump (Figure 3a-b). The entire batch of tracer was injected after about 5 minutes of continuous pumping including an after flush of water to dissolve the tracer sludge that have accumulated at the bottom of the tracer solution tank. Brine injection into the well, estimated at 90 kg/s, continued during tracer injection. The wellhead pressure of MT2RD remained constant while the tracer was pumped into the well.

Sampling of tracer from production wells was carried out by installing ½" diameter coiled stainless steel (SS316) tubing into the two-phase pipeline sampling point of each individual production well. The coiled tubing are immersed in plastic drums filled with cold water to allow the collected samples to cool down to less than 30°C. The samples are collected in 250-mL polyethylene bottles with sealed caps.

About 2.5 ml of 1.5 N HCL is added to the sample to prevent silica precipitation. In the first two months after injection, sampling was conducted daily. Sampling frequency was reduced to every other day from two months to eight months after injection. This was further reduced to three times weekly after eight months. Adjustment in sampling frequency cannot be implemented as often as desired due to the slow turnover of results. A strategy of frequent sampling but selective analysis was employed to address this difficulty.

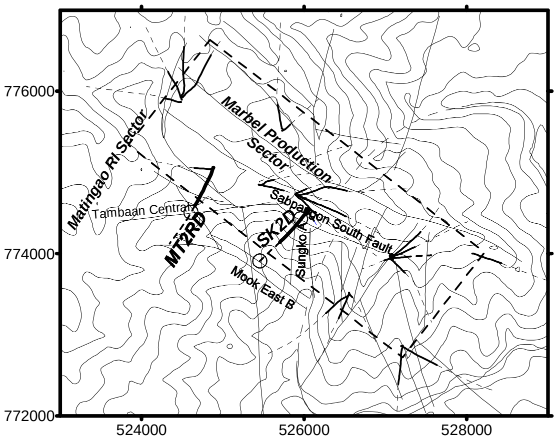

Figure 2. Enlarged view of well locations of MT2RD and SK2D showing the structures attributed to the permeable horizons of the wells. The distances between the permeable horizons between injection well and production well are used in the modeling calculations.

The samples are sent to LGPF Geoservices Laboratory in Ormoc, Leyte for analysis. The instrument used is Shimadzu LC10A1 High Performance Liquid Chromatography (HPLC) with Merck Chromolith SpeedROD RP-18e 50 x 4.6 mm column and fluorescence detector set at 333 nm excitation (285 nm emissions). The mobile phase used is methanol phosphate buffer (77:33) with 5 mMol tetrabutyl. The detection limit of the analysis is 0.5 ppb.

3. DATA AND MODELING

SK2D tracer results sent by LGPF Geoservices Laboratory in parts per billion (ppb) are recalculated to g/L or kg/m3 concentration. Since background tracer concentration is essentially zero, the analytical results are used as is without background correction or correction for thermal decay. Date of sampling is likewise re-computed to seconds after injection. Figure 4 shows the plot of 1,6-NDS concentrations against time in well SK2D. The maximum concentration recovered from the test in SK2D is 45E-6 g/Land occurs about 5 months after injection. The tracer breakthrough started about three weeks after injection and extended to more than 9 months without returning to the baseline concentration.

To determine the total mass of tracer recovered from the well, the area under the breakthrough curve is integrated and multiplied by the discharge flow of SK2D. Integration is done using TRMASS (Arason, 1993) computer program. Based on the 65 kg/s discharge flow of the well, total tracer mass recovered was calculated at ~11% or 44 kg of the 400 kilograms 1,6-NDS injected. However, the available data is incomplete and did not generate a full tracer breakthrough curve. This implies that the estimate of tracer recovered from area integration of the data curve is an underestimation of the true mass recovery. To better approximate the mass recovery, tracer data inversion and modeling is employed. The effect of re-injection fluid to the production temperature of SK2D is calculated using the results of tracer data inversion.

Figure 3. Photograph above show injection of 400 kilograms 1,6 naphthalene di-sulphonate (1,6-NDS) tracer in well MT2RD. The tracer is dissolved in 5000 liters of water and injected through the wing valve using 4TUT pump. Injection of the tracer solution is completed after in less than 5 minutes

Table 1. Model parameters used in the calculations. The distance (x) represents the distance between major permeable horizon in MT2RD and inferred feed zones in well SK2D.

Pulse	x	u	D	m
1	1100	0.7471E-04	0.1807E-01	0.7791E-01
2	1300	0.4805E-03	0.2678E-01	0.3304E-02
3	1400	0.6909E-04	0.2062E-03	0.9159E-03

3.1 Tracer data inversion

To interpret the tracer data from SK2D, a simple one-dimensional flow-channel tracer transport model is used as basis fro interpretation. The model assumes the flow between injection and production wells may be approximated by one-dimensional flow in flow channels. These flow-channels may be parts of near-vertical fracture-zones or parts of horizontal inter-beds or layers (Axelsson, 1995). They may be envisioned as being delineated by the boundaries of these structures and flow-field streamlines. In some cases more than one channel may be assumed to connect an injection and a production well, i.e. connecting different feed-zones in the wells involved. The working equation for the model is shown in Equation 1.

$$c(t) = \frac{uM}{Q} \frac{1}{2\sqrt{\pi D t}} e^{-(x-ut)^2/4Dt} \qquad (1)$$

Where, velocity u = q/ρAϕ, q = injection flow-rate in the channel, dispersion D = αLu (diffusion neglected), αL – is the longitudinal dispersivity, M is the tracer mass recovered, c(t) is the tracer concentration in the production well fluid, Q is the production rate (kg/s) and x is the distance between the wells involved. Conservation of the tracer according to c·Q = C·q, has been assumed in this model. The computer program TRINV (Arason, 1993) is used to do the inversion calculation on the tracer test data of SK2D.

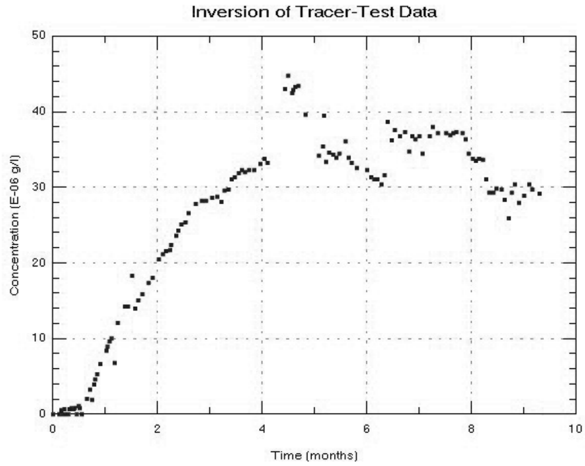

Figure 4 Raw tracer data plotted versus time. No background and decay correction is needed for the data because the tracer has zero concentration initially in the reservoir and does not degrade at temperatures below 300°C.

Actual data and simulated tracer curve based on the one-dimensional flow channel tracer transport model are shown in Figure 5. The coefficient of determination for the model parameters relative to actual data is 97%. The curve was calculated from the model parameters shown in Table 1. It is assumed in the model that tracer breakthroughs arrive in three pulses or channels. These channels represent the structural passageways connecting MT2RD to SK2D where the tracer was transported. The mass contribution (ratio with respect to injected tracer mass) of each flow channel is shown in Table 2, including the cross-sectional area x porosity and the assumed porosity for each flow channel. The total tracer recovered in SK2D from the three pulses total 20.39%. One flow channel (Tambaan Fault–Sabpangon South Fault), account for 96% of the total tracer recovered.

Table 2. Amount in percent of tracer recovered per tracer pulse in well SK2D and the inferred structural conduit. The assumed porosity per channel is 10%.

Pulse Number	Postulated Path	Tracer Recovery (%)	$A\phi$	Assumed Porosity
1	Tambaan – Sabpangon South	19.69	301	10
2	Tambaan – Sungko A	0.39	1	10
3	Tambaan – Mook East A	0.31	4	10

3.2 Cooling predictions

The results of tracer inversion calculations are used to predict the effect of re-injection fluid to the production temperature of SK2D. Cooling of production wells is not uniquely determined by flow-path volume but also depends on surface area and porosity of flow channel. Large surface area leads to slow cooling and vice versa. The Program TRCOOL (Axelsson, 1993) is used for the cooling predictions in SK2D. The equation used for modeling cooling in production well is shown in Equations 2-4.

$$T(t) = T_0 - \frac{q}{Q}(T_0 - T_i)\left[1 - erf\left\{\frac{kxh}{c_w q\sqrt{k(t - x/\beta)}}\right\}\right] \qquad (2)$$

$$\beta = \frac{qc_w}{\langle pc \rangle_f hb} \qquad (3)$$

$$\langle pc \rangle_f = p_w c_w \phi + p_r c_r (1 - \phi) \qquad (4)$$

where T(t) = production temperature, T0 = initial reservoir temp. Ti = injection temp, q = injection rate, Q = production rate, h = channel width, b = channel thickness, k = thermal conductivity of reservoir rock, K = thermal diffusivity of rock, ρ and c are density and heat capacity of water (w) and rock (r).

The result of cooling prediction in SK2D production temperature is shown in Figure 6. The production rate of SK2D used in the calculation is 65 kg/s, while the injection rate into MT1RD is assumed to be constant at 90 kg/s. The stable measured temperature in SK2D is 253°C and is assumed to be the initial production temperature of the well. Brine injected in MT2RD is about 150°C starting middle of 1999, but was higher at 170°C in 1997. For simplicity, the flow channel thickness and width are assumed to be the same and is equal to the square root of the quotient of the cross section area x porosity product divided by the porosity. Since one of the flow channels clearly dominates the rest of the flow channels in terms of tracer returns, only the effect of this channel is used in the calculation.

The model predicts that the production temperature would drop abruptly from 253°C to 235°C five years from start of injection (mid-1999). A four-year relatively stable production temperature precedes this drop. However, the 235°C production temperature would persist and decline at a very slow rate beyond the five years (231°C in ten years) provided injection flow into MT2RD remained at about 90 kg/s and injected brine temperature does not change.

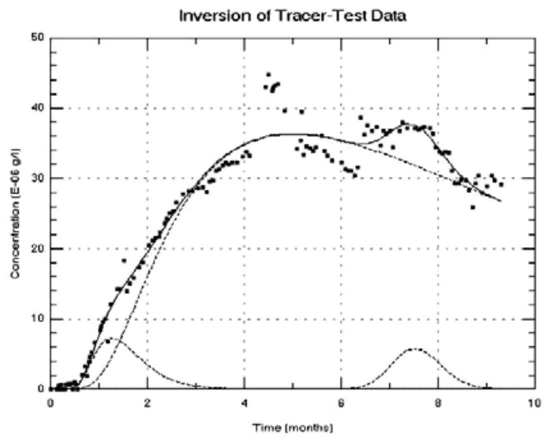

Figure 5 Result of simple one-dimensional channel tracer transport model superimposed on actual tracer data. The coefficient of determination of the model and actual data is 97%. Three tracer pulses may be responsible for the tracer curve behavior in well SK2D.

To test the prediction, the saturated liquid temperature equivalent to the measured production enthalpy of the well since 1999 is plotted along the predicted temperature of the model. From a temperature range of 255°C – 260°C from 1999 to 2001, the temperature appeared to have decline to 240°C – 245°C beginning 2002. The timing and behavior of the temperature decline agrees with the abrupt decline in production temperature predicted from the model.

4. DISCUSSION

The amount of injected brine returning to SK2D from MT2RD is substantial. At 20%, this translates to about 17 kg/s of flow out of the 78 kg/s total production of the well. However, despite the substantial returns, the mean velocity of the re-injection returns is slow and highly dispersed. There appears to be a fast tracer breakthrough occurring about one month after injection but the volume of return is minimal (< 1 kg/s) and will probably cause minimal decline on long-term production temperature. If the predictions of the model are true, a maximum of 2 MW decline in power output in the well is expected after five years. However, considering that SK2D is initially producing from a high enthalpy steam dominated zone and eventually lost contribution from the latter can complicate the future production in this well. If the re-injection fluid is entering through the steam-dominated zone, the loss in steam production from the well could be more substantial compared to a purely cooling effect on the liquid feed zones.

Some aspects of the working models can be enhanced to make the predictions closer to real field observations. One approach would be to obtain independent estimates of porosity. This can be calculated from existing micro-gravity measurements conducted in the field. Similarly, by studying the dimensions/extent of permeable horizons in the injection and production well to provide reasonable assumptions on the thickness and width of the flow channels. Also a worst case and best-case scenario can be simulated as suggested by Arnorsson (1995) to determine the range of possibilities in the predictions. Existing temperature data is also valuable in calibrating the models.

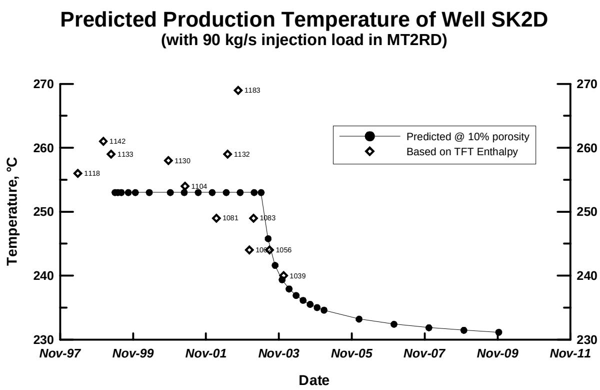

Figure 6 Results of cooling prediction in production temperature of well SK2D based on the re-injection fluid volume predicted by the model. Black diamonds represent the temperature and corresponding enthalpy of discharge of SK2D since 1999.

Other flow models (such as lump parameter modeling, semi-analytical semi-numerical modeling, etc.) can also be explored to have an idea of the minimum and maximum production temperature effects caused by the re-injection breakthrough. The idea is to predict the fluid temperature of the production well at the current injection load to a lower or higher load and eventually find the scheme that best sustains well production.

5. CONCLUSION

1,6 Naphthalene Disulfonate tracer injected in MT2RD was recovered in well SK2D. Maximum tracer recovered reached 45 ppb in the discharge and persisted for more than 9 months. A total of 20.39% of tracer injected in MT2RD reached SK2D based on simple one-dimensional flow-channel tracer transport model.

With the average injection load of 90 kg/s in MT2RD, the production temperature of SK2D will decline from a baseline of 253°C to 235°C five years after start of injection and decline and stabilize to about 231°C in ten years. An estimated decline in power output of 2 MW from baseline will occur in SK2D within ten years assuming current injection load and constant mass discharge from the well.

Because of the large volume of injected fluid returning to the production zone from MT2RD, reducing the injection load in this well is recommended. Drilling of re-injection well far from Marbel production sector is the long-term solution to re-injection problems in Mindanao Geothermal production Field.

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