PROCEEDINGS, Thirtieth Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, January 31-February 2, 2005
SGP-TR-176

TRACER TESTING AT MORI GEOTHERMAL FIELD, JAPAN, USING AROMATIC COMPOUNDS

Masato Watanabe[1], Fumiaki Arai[1], Daisuke Fukuda[1], Mikihiro Asanuma[1], Yasuyuki Hishi[1] and Jiro Tsutsumi [2]

[1]JMC Geothermal Engineering Co., Ltd.,
101-1 Hosoyachi, Ukai,
Takizawa, Iwate, Japan
e-mail: watanabe@geothermal.co.jp
[2]Hokkaido Power Engineering Co., Ltd.,
108-5 Nigorikawa, Mori,
Hokkaido, Japan

ABSTRACT

The three tracers were simultaneously injected into the three different re-injection wells: toluenesulfonate (methylbenzensulfonate), 1-naphthalene sulfonate and 1,5-naphthalene disulfonate. Toluenesulfonate was injected into NF-6 having injection points in the southwest part of caldera wall, then detected in the three wells having their feed points below injection point of NF-6. 1-Naphthalene sulfonate and 1,5-naphthalene disulfonate were injected into NF-2 and NF-8, respectively, and then detected in all the production wells in the field. The injection points of NF-2 and NF-8 are in the southeast part of caldera wall, and very close each other. Although we had expected that tracer flow patterns of 1-naphthalene sulfonate and 1,5-naphthalene disulfonate would be similar, the pattern of 1-naphthalene sulfonate returns was different from that of 1,5-naphthalene disulfonate. To illustrate the each tracer flow comprehensively, we tried to visualize them three-dimensionally in the view of mass transfer. The contour plots showed that most of the 1,5-naphthalene disulfonate flowed downward to the depth of the reservoir along the southeast part of caldera wall in a short period of time, and the 1-naphthalene sulfonate spread not only to the depth also horizontally to the intermediate depth and shallow region.

INTRODUCTION

The Mori liquid-dominated geothermal field is located in the Nigorikawa Caldera in southwest Hokkaido, Japan (Figure 1). The Mori geothermal power station started power generation of 50 MWe with six production wells and seven re-injection wells in 1982. Ten production wells and nine injection wells are presently used.

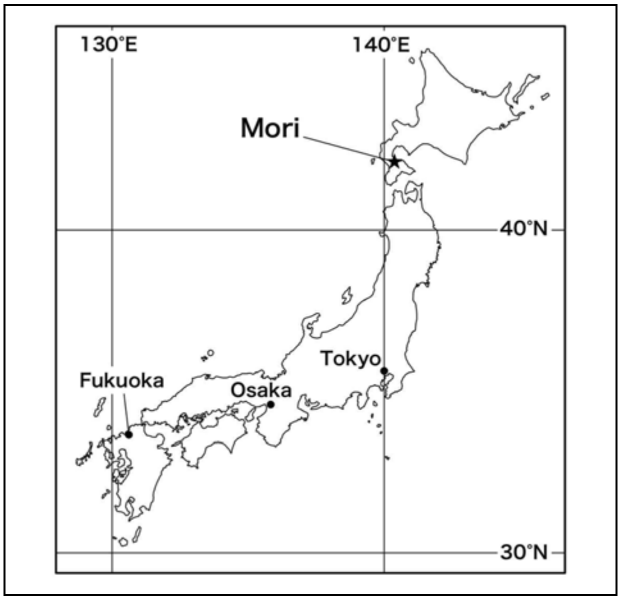

Figure. 1. Location of the Mori geothermal field.

The Nigorikawa Caldera was formed about 12,000 years ago (e.g. Yanai et al., 1992). The caldera is shaped like a funnel, about 3 km in diameter at the surface (Figure 2). Below about -2,000 masl, the caldera has a vertical vent, about 300 to 500 m in diameter, infilled with post-caldera intrusion (Kurozumi and Doi, 2003). The outside of the caldera is comprised of Tertiary and pre-Tertiary formations covered with Quaternary sediments.

The production wells in the reservoir are divided into three groups as follows:
(1) Deep production wells: having feed points in the deep part of the caldera wall (ND-7, ND-11, NF-1, NF-10, NF-11 and NF-12, 2,100-2,900 m depth).
(2) Shallow production wells: having feed points in the pre-Tertiary formation outside of the caldera at

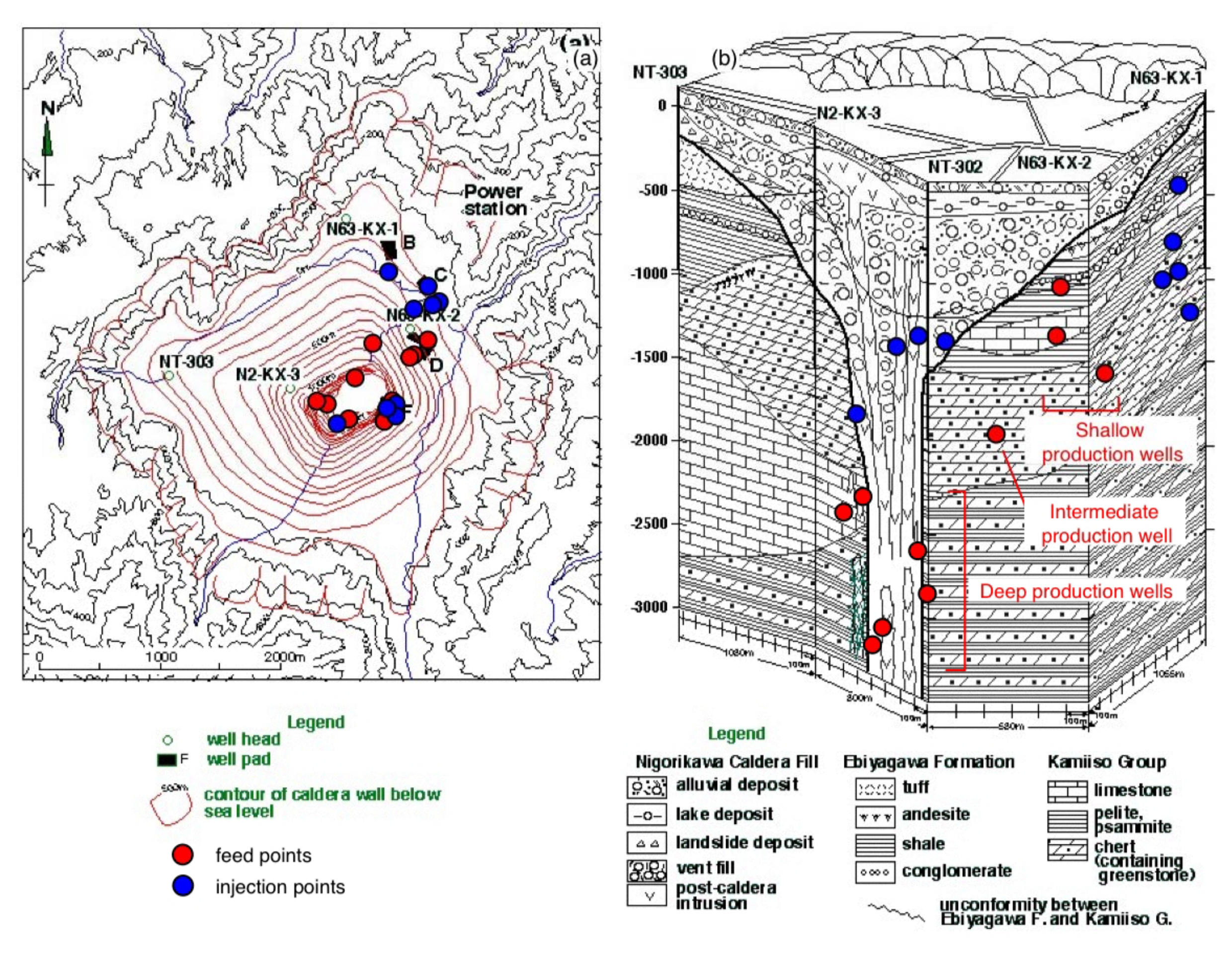

Figure. 2. (a) Isocontour map of the caldera wall (after Kurozumi and Doi, 1994). (b) Schematic cross section of the Nigorikawa caldera (after Kurozumi and Doi, 1993).

shallow depth (ND-5, ND-8 and ND-9, 500-1,000 m depth).
(3) Intermediate-depth production well: having feed point in north part of the caldera wall at intermediate depth (ND-1, 1300 m depth).
Additionally, the injection points are divided roughly inside and outside of the caldera.

Most of fluids are produced from a fracture network in the caldera and more than a half of total injection fluid are returned back to the same fracture network. Therefore, it is important to evaluate quantitatively the returns of injected water for the reservoir management.

Tracer test has been one of the most important methods to evaluate the injection returns conducted periodically in the field. The potassium iodine (KI) and potassium bromine (KBr) were used before May 2000. However, the sensitive detection of KI and KBr became difficult because of the accumulation of them by a number of injections. To trace the injection sensitively, we started to use aromatic compounds in October 2000 (Hishi et al., 2001). The compounds are more detectable than KI and KBr, and thus give more practical information to us.

This paper presents the results from the tracer tests in which three aromatic compounds were injected almost simultaneously into the three different wells in 2004.

METHOD

The three tracers were injected into the three different re-injection wells: toluenesulfonate (methylbenzen-sulfonate), 1-naphthalene sulfonate and 1,5-naphthalene disulfonate. The three tracers were injected in series within six hours on 26 August 2004: 473 kg of toluenesulfonate was injected into well NF-6, 300 kg of 1-naphthalene sulfonate was injected into well NF-2, and 285 kg of 1,5-naphthalene disulfonate was injected into well NF-8. The each tracer was dissolved with about 2.5 kl of brine (re-injection water) in a mixer tank equipped with a pump (Figure 3). The each tracer was injected using the pump in 20-30 minutes.

Figure 3. Photograph of the tracer mixer tank used in the Mori geothermal field. The tank is 3 kl in volume and equipped with a pump for mixing and injecting the tracer solution.

All of the production wells in the field were subsequently monitored for the three tracers over the subsequent three months. The wells were sampled once per day for one week after injection, and then in low frequency as time passed. We collected 25 samples (flashed brine) in 100ml polyethylene bottles for each production wells during the monitoring period.

The samples were analyzed by High Performance Liquid Chromatograph (HPLC) equipped with an ultraviolet (UV) detector (Shimadzu, SPD-6A), fluorescence detector (Shimadzu, RF-10A$_{XL}$) and C-18 column (Shimadzu, VP-ODS). Toluenesulfonate and naphthalenes were analyzed with the UV detector and the fluorescence detector, respectively. Excitation and emission wavelength of the fluorescence detector were set 290 nm and 340 nm, respectively. The mobile phase was consisted of 35 wt% methanol solution buffered 25 mmol KH_2PO_4.

RESULTS AND DISCUSSION

The return curves for toluenesulfonate, 1-naphthalene sulfonate and 1,5-naphthalene disulfonate are shown in Figure 4. To compare the return mass of the tracers, we use tracer production rate (g/h) instead of concentration in samples.

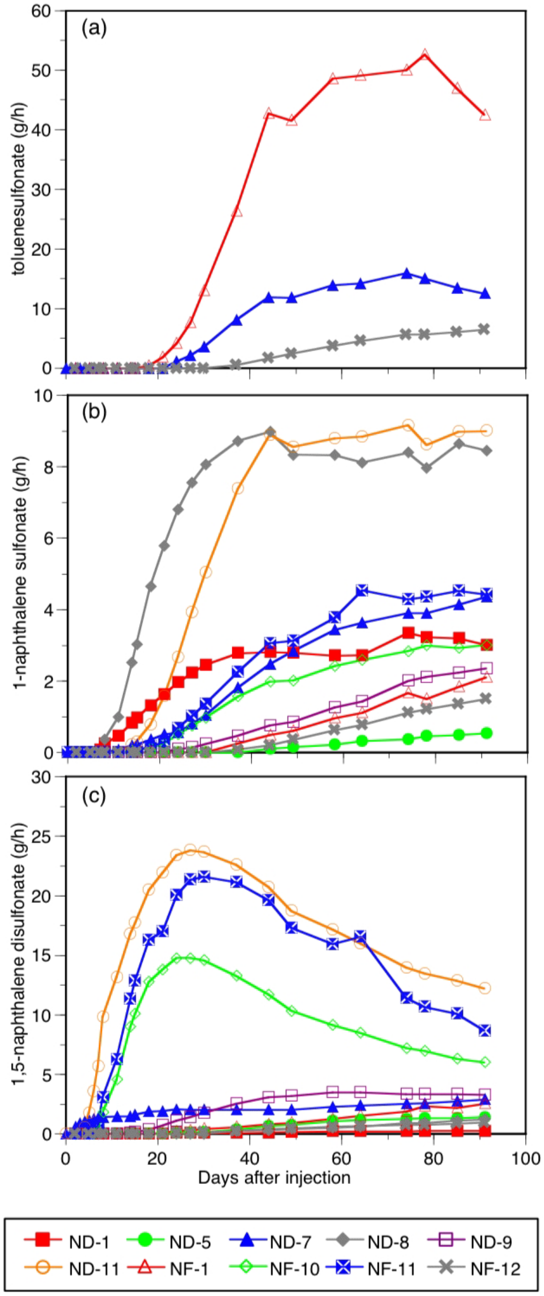

Figure 4. Tracer return curves; (a) toluenesulfonate (injected into NF-6), (b) 1-naphthalene sulfonate (injected into NF-2) and (c) 1,5-naphthalene disulfonate (injected into NF-8).

Breakthrough from a re-injection well to all the production wells were observed in the tests for NF-2 and NF-8. Breakthrough had been observed from a half of production wells in the previous tests for NF-2 and NF-8 using KI and KBr. Because KI and KBr were contained originally in the geothermal water, the background concentrations of them were rather high. In contrast, aromatic compounds were not contained originally in the geothermal fluid. Furthermore, the detection limits of aromatic compounds are significantly lower than that of KI and KBr. Therefore, the tracer tests using aromatic compounds revealed the previously undetected breakthroughs.

Test on NF-6

Toluenesulfonate was injected into NF-6, and detected in ND-7, NF-1 and NF-12. As Figure 4 (a) shows, the arrivals of the tracer were seen first in NF-1, secondly in ND-7 and finally in NF-12. The highest and second highest tracer production rates were observed in NF-1 and ND-7, respectively. NF-12 showed the lowest tracer production rate. The above results consist with the distance between the injection point and feed points of the three production wells; the shorter the distance is, the faster the tracer arrived and the higher the production rate was.

The injection point and feed points distribute in the southwest part of the caldera wall. Additionally, because the injection point was shallower than the feed points, the tracer obviously moved downward in the southwest part of the caldera wall.

Test on NF-2

1-Naphthalene sulfonate, injected into NF-2, was returned from all production wells. As Figure 4 (b) shows, the strongest returns were observed in wells ND-8 and ND-11. The tracer production rates of ND-8 and ND-11 increased more rapidly than the other wells. The flow paths from NF-2 to ND-8 and ND-11 are quite different in direction. The injection point of NF-2 and feed point of ND-11 are located in the southeast part of caldera wall, and the injection point is shallower than the feed point. As with the case of NF-6 test, a part of the tracer moved downward along caldera wall. On the other hand, the feed point of ND-8 is in a pre-Tertiary formation outside of the caldera. Furthermore, because the injection point and the feed point are at the similar depth, another horizontal path exists in the pre-Tertiary formation.

Test on NF-8

As with the test of NF-2, 1,5-naphthalene disulfonate injected into NF-8 was returned from the all production wells. As Figure 4 (c) shows, the returns were stronger to ND-11, NF-10 and NF-11 than to the other production wells. The return curves of the three wells showed their peaks of tracer production rates in 27-30 days after injection. The feed points of ND-11 and NF-11 are located in the southeast part of caldera wall, and that of NF-10 is located in the north part of the caldera wall. These feed points are at the deep part of the caldera wall. The injection point of NF-8 is located in the southeast of caldera wall, and is shallower than these feed points. This indicates that the tracer moved downward along the southeast part of the caldera,

As mentioned above, the results from the tests on NF-2 and NF-8 showed the strong tracer flows toward the deep feed points around the caldera wall, and the moderate flows in the pre-Tertiary formation. The results also showed a variety of return-curve patterns (Figure 4 (b) and (c)), although the injection points of NF-2 and NF-8 are very close each other; they are in the southeast part of caldera wall at about 900 m depth. On the other hand, as Figure 2 shows, the locations of feed points are of wide distribution. To understand the tracer flows spreading widely, we tried to visualize them three-dimensionally in the view of mass transfer.

Contour plots of 1-naphthalene sulfonate and 1,5-naphthalene disulfonate production rates

To follow the mass transfer of 1,5-naphthalene disulfonate (the tracer of NF-8) and 1-naphthalene sulfonate (the tracer of NF-2), we tried to draw the contour plots of the tracer production rates. The contour plots of each tracer were drawn at 5, 14, 30, 58 and 91 days after tracer injection. We aligned these five contour plots with time in Figure 5 and 6.

In order to make the contour plots, we created a rectangular grid model including all feed points with a software (Tecplot 10). Then we set the tracer production rates on the feed points in the model. The colored contour plots were drawn base on the ordered data interpolated by Kriging.

Figure 5 and 6 show the contour plots of the production rates of 1,5-naphthalene and 1-naphthalene sulfonate, respectively. Note that the scales of the plots are different; maximum scales are 25 g/h and 10 g/h for 1,5-naphthalene disulfonate and 1-naphthalene sulfonate, respectively.

Figure 5 shows that the higher tracer production area is along the southeast part of caldera wall. The highest value (>20 g/h) was seen in deep part of the caldera wall in 30 days after tracer injection. Therefore, most of the tracer flowed downward and was produced from the deep wells. In contrast, the tracer production rates in the pre-Tertiary formation are much lower than those in the deep part of caldera. This indicates the higher permeability between NF-8 and deep feed points in the southeast part of caldera wall.

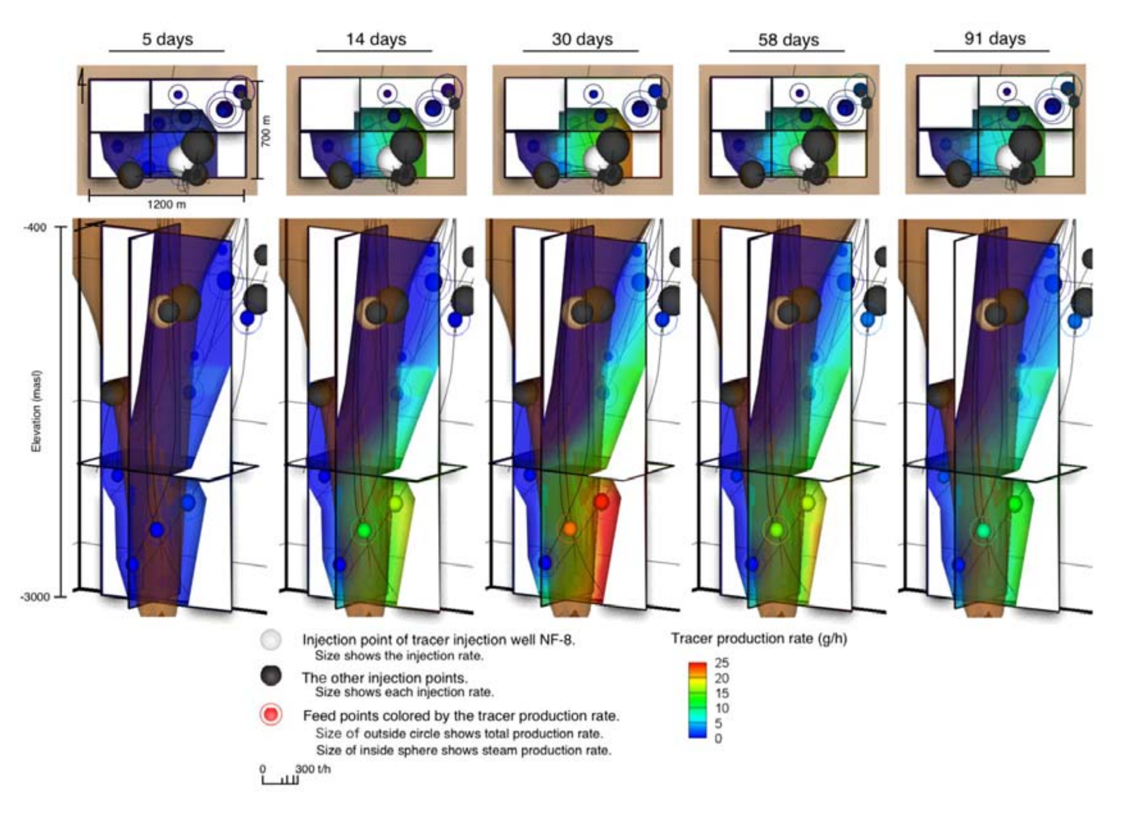

Figure 5. Contour plots of 1,5-naphthalene disulfonate production rate in order of time (5, 14, 30, 58 and 91 days after tracer injection). The upper contour plots are planes at the depth of 2,000 m.

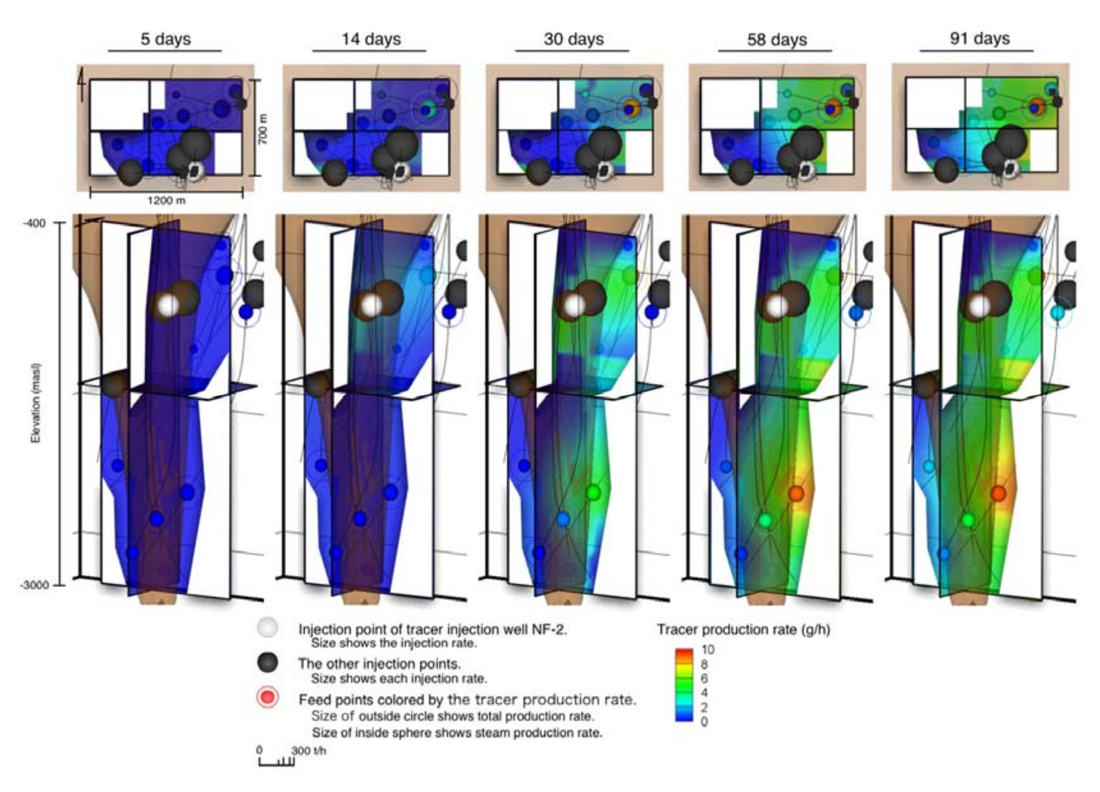

Figure 6. Contour plots of 1-naphthalene sulfonate production rate in order of time (5, 14, 30, 58 and 91 days after tracer injection). The upper contour plots are planes at the depth of 1,500 m

Figure 6 showed that the higher tracer production rate was found not only in deep region close to caldera wall also in the shallow pre-Tertiary formation. The highest value (ca. 8 g/h) was seen in the shallow and deep region in 58 days after tracer injection. Furthermore, an appreciable change is not seen between the contour plots of 58 days and 91 days. Additionally, the intermediate value (ca. 5 g/h) is seen widely. These results indicated that the 1-naphthalene sulfonate spread widely and slowly not only to deep region also to intermediate depth and shallow region.

The injection points of NF-2 and NF-8 were very close each other, and almost same weight of tracers was injected into them. However, the tracer flow pattern of 1-naphthalene sulfonate was different from that of 1,5-naphthalene disulfonate as found in the contour plots of tracer production rate. These observations may be caused by injection into NF-5. NF-5 has injection point close to those of NF-2 and NF-8, and the largest amount of brine was injected into NF-5 (ca. 300 t/h) in the field. Therefore, the tracer flows may have been affected by the injection of NF-5. Because a tracer test on NF-5 is untried for several years, we believe that it is important to conduct a tracer test targeting NF-5 and understand the interference among NF-2, NF-8 and NF-5.

CONCLUSION

On 26 August 2004, the three tracer tests targeting three injection wells were conducted simultaneously using toluenesulfonate, 1-naphthalene sulfonate and 1,5-naphthalene disulfonate. As results from the tests, breakthroughs undiscovered in the past tracer tests using KI and KBr were found. Toluenesulfonate injected into NF-6 having injection points in the southwest part of caldera wall was produced from the three wells having their feed points below the injection points of NF-6. Therefore, the tracer moved downward in the southwest part of the caldera wall. 1-Naphthalene sulfonate and 1,5-naphthalene disulfonate were injected into NF-2 and NF-8, respectively. The injection points of NF-2 and NF-8 are in the southeast part of caldera wall, and very close each other. The both tracers were detected in all the production wells in the field, but the patterns of the each tracer return were different. To illustrate the tracer flows comprehensively, we visualized them three-dimensionally in the view of mass transfer. The contour plot of tracer production rate indicated the characteristics of tracer returns as follows:

(1) The most of 1,5-naphthalene disulfonate flow downward to the depth of the reservoir along the southeast part of caldera wall in a short period of time.

(2) The 1-naphthalene sulfonate spread not only to the depth also horizontally to the intermediate depth and shallow region.

The geochemical temperatures of produced fluids have been almost constant under the current condition of injection. Therefore, current injection rates are acceptable. However, the returns of largest injection into NF-5 have not been evaluated recently, so that it is important to conduct tracer test targeting NF-5 next time.

ACKNOWLEDGMENTS

Hokkaido Power Engineering Co. Ltd. and Hokkaido Electric Power Co. Inc. allowed us to use the results of the tracer tests and much of their various information. The authors thank very much persons for their supports and advices.

REFERENCES

Hishi, Y., Fukuda, D., Asanuma, M., Kobayashi, K. and Kasai, K. (2001), “Tracer testing at the liquid dominated reservoirs, using aromatic compounds (in Japanese).” *Abstract, 2001, Meeting of the Geothermal Soc. Japan,* P32.

Kurozumi, H. and Doi, N. (1993), “Inner Structure of the Nigorikawa Caldera.” *Abstract, 1993, No.2 Meeting of the Vol. Soc. Japan,* A14

Kurozumi, H. and Doi, N. (1994), “Inner Structure of the Nigorikawa Caldera (Part 2).” *Abstract, 1994, No.2 Meeting of the Vol. Soc. Japan,* G14

Kurozumi, H. and Doi, N. (2003), “Inner Structure of the Nigorikawa Caldera, Hokkaido, Japan.” *Bull. Volcano. Soc. Japan*, **Vol.48 (3)**, 259-274. (in Japanese with English abstract)

Yanai, S., Ganzawa, Y. and Komori, Y. (1992), “The Stratigraphy and Distribution of the Nigorikawa Tephra, Latest Glacial Age Time-marker in Southwest Hokkaido.” *Jour. Geol. Soc. Japan*, **Vol.98, No. 2**, 125-136