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The First Two-Phase Tracer Tests at the Matsukawa Vapor-Dominated Geothermal Field, Northeast Japan

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ABSTRACT

As injection was practiced in the Matsukawa geothermal field, northeast Japan, the necessity of a tracer test emerged to evaluate the flow paths and recoveries of injected water. The Matsukawa reservoir being vapor-dominated, vapor-phase and two-phase tracers were considered for the first tracer test at this field. Sulfur hexafluoride, hydrofluorocarbons (vapor-phase tracers), and alcohols (two-phase tracers) were examined in terms of their practical use. The alcohols (methanol, ethanol, n-propanol and i-propanol) were selected since their properties were suitable for two-phase tracers.

The returns of alcohols were detected by five tests from 2000 to 2003 and smooth return curves were obtained. The flow paths and recoveries were evaluated from the tests. The results of the tests using mixed solutions of ethanol and i-propanol showed variation in the ethanol / i-propanol ratios and different peak times of ethanol and i-propanol, which could be caused by the process of boiling and two-phase flow in the vapor-dominated reservoir.

1. INTRODUCTION

1.1 The Matsukawa Geothermal Field

The Matsukawa Geothermal Power Station is located in the Hachimantai volcanic area, Iwate prefecture, northeast Japan (Figures 1 and 2). It started power generation in October 1966 with 9.5 MWe as the first commercial geothermal power station in Japan. The capacity has been increased gradually up to 23.5 MWe by June 1993. Usually, half of about ten production wells produce saturated steam after water injection, although at first they produced superheated steam. Therefore, it is important to monitor the recovery of injected water in this field.

1.2 Injection Tests Including Tracer Tests

A few production wells were used for the injection tests, since there were no re-injection wells in the field. Steam condensate, stream water, brine and their mixture were injected. Long-term injection has been carried out at well MR-1 for 15 years (from March 1988 to July 2003). The range of injection rates has been from 10 t/h to 130 t/h. Short-term (several months) injection tests were also conducted for wells M-6 and M-13. Fluid was injected at the average rates of 20 t/h for well M-6 (from February to October 2000), and 40 t/h for well M-13 (from October to November 2002). The test at well M-6 was terminated when increased brine production was observed from well M-8.

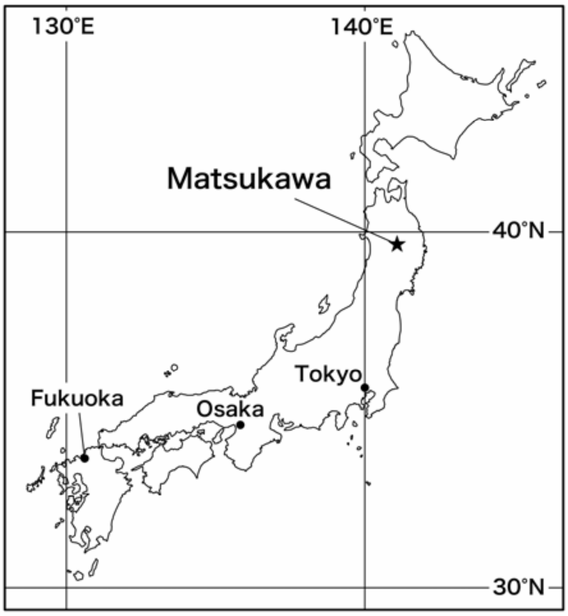

Figure 1. The location of the Matsukawa geothermal field.

1.3 Monitoring of Injected Water

Geochemical and geophysical surveys clearly detected the returns of injected waters for the short-term tests: e.g. increase in non-condensable gas (NCG) concentrations, decrease in steam temperatures and beginning of brine production. The surveys for the long-term injection lacked noticeable signs of returns except during the primary period of injection. It was especially difficult to evaluate the injection flow toward the relatively new wells which started production after the beginning of the injection, since the reservoir conditions around the wells could have been changed by the long-term injection.

For tracing and quantitative estimation of the injection flow in the vapor-dominated reservoir, two-phase and vapor-phase tracer tests were considered as the best method. Accordingly, we selected alcohols as the two-phase tracers. This paper presents the basic results of five tests conducted from 2000 to 2003.

2. SELECTION OF TRACERS

Sulfur hexafluoride (SF_6), hydrofluorocarbons (HFCs, e.g. R-23 and R-134a) and hydrochlorofluorocarbon (HCFCs, e.g. R-12 and R-13) have been used extensively as vapor-phase tracers at The Geysers, California, U.S.A. (Adams et al., 1991a, b and 2001; Adams, 1995; Beall et al., 1994, 1998; Voge et al., 1994) and Wairakei, N.Z. (Glover and Kim, 1993). The potential of alcohols as two-phase tracers were reported by Adams (1995) and Adams et al. (2000), although their practical use in the field had not been tested. Lovelock (2001) showed the usefulness of alcohols in tracer flow testing, where i-propanol was used at temperatures up to 225°C.

Based on these previous studies, we examined the use of SF_6 and HFCs as vapor-phase tracers, and alcohols (e.g. methanol, ethanol, i-propanol and n-propanol) as two-phase tracers. Alcohols were selected because of the properties discussed below. HCFCs were excluded since they are ozone depleting substances.

2.1 Thermal Stabilities and Detection Limits of SF_6, HFCs and Alcohols

Adams et al. (2000) reported that SF_6 and methanol showed high stability (< 5% decay) at temperatures up to about 300°C, pHs of 3 to 7 and for durations of up to two weeks. Ethanol and n-propanol showed decay of 10-20%. R-134a, one of HFCs, showed 10 - 50% decay at temperatures up to 290°C and durations up to 19 days (Adams et al., 2001).

Sulfur hexafluoride and HFCs are detectable in the order of ppb to ppt using a gas chromatograph (GC); in contrast, our detection limits of alcohols are 0.1 to 0.5 ppm using a GC. Therefore SF_6 is superior to alcohols in terms of thermal stability and detection limit.

2.2 Properties of SF_6, HFCs and Alcohols Related to Injection, Sampling and Analysis

Despite their theoretical advantages, SF_6 and HFCs have some disadvantages for injection and sampling. It is difficult to inject the all of the gas into formations from the surface. For example, in order to optimize the injection of SF_6 gas tracer, Glover and Kim (1993) employed a downhole injection method in which a glass ampoule containing SF_6 was broken at the desired depth during water injection. Furthermore, vapor-phase tracers do not follow the same path as the injected water, which takes time to boil in the reservoir (Adams, 1995).

Also, SF_6 and HFCs are collected into specially sealed and evacuated flasks containing an alkali solution, as used for general steam sampling. This is not suitable for frequent sampling, e.g.: once an hour to once a day for several wells. In contrast, alcohols have advantages as two-phase tracers:

1) The vapor pressures are similar to that of water;

2) Alcohols are miscible or significantly soluble in water;

3) Several alcohols with different physical properties are available: e.g. methanol, ethanol, n-propanol and i-propanol.

Being liquid at atmospheric temperature and pressure, alcohols are injected easily using a simple pump as is the case with liquid-phase tracers. Since alcohols are miscible or significantly soluble in water and their vapor pressures are similar to that of water, it is expected that alcohols flow and boil in the vapor-dominated reservoir as the injected water. Being condensed at atmospheric temperatures, alcohols are collected quite easily into screw-cap bottles as steam condensate. Furthermore, it is possible to use different alcohols at the same time for the different wells, or mix them to take advantage of their different vapor pressures for investigating the boiling process of the injected water.

In addition to the advantages mentioned above, we have developed a direct-injection method for alcohol analysis by modifying an existing gas chromatograph. This technique shows greater sensitivity than the head-space gas chromatographic method used in tracer flow testing (Lovelock, 2001). For these reason, alcohols were employed as tracers at the Matsukawa field, even though SF_6 and HFCs are more thermally stable and detectable as shown by the results of previous studies. We also thought that alcohols would not decay significantly at moderate temperatures found in the Matsukawa field (< 260°C), unlike the result of the experiments at the high temperature up to 300°C by Adams et al., (2000).

3. METHOD

3.1 Tracer Injection

For a well with negative wellhead pressures, tracers were injected directly from metal barrels at the wellhead. For wells with positive wellhead pressures, a pump was used. The injection took less than 10 minutes for a negative wellhead pressure and 20 to 45 minutes for the positive ones. Methanol, ethanol, i-propanol, n-propanol and various mixtures of these were used. These solutions were diluted to 60% because of the inflammability of alcohols. In order to make detection easier, about 100 kg to 3,000 kg of alcohols were used per test (Table 1). Water injection continued during tracer tests at the rates ranging from 10 t/h to 40 t/h.

3.2 Sampling

Cooling coils were connected to the steam lines and 100 ml of condensates were collected into screw-cap bottles. Samples were treated with 0.1 ml of 5% zinc acetate solution to precipitate H_2S to protect the GC column. Sampling for a well was done within 10 minutes. Sampling continued for several days to more than two months. The sampling frequency ranged from approximately one hour at the beginning of the tests to several days after a few weeks.

3.3 Analysis

The analyses were performed on a Shimadzu GC-14B gas chromatograph equipped with a flame ionization detector. Separation was achieved with a 3 m x 3 mm column containing 80/120 mesh Carbopack, and the carrier gas of nitrogen. Samples and calibrators (1-5 µl) were injected into the GC directly by an auto injector. Alcohol concentrations were calculated by comparing peak area values of samples and calibrators. The detection limits were 0.1 ppm for ethanol, i-propanol and n-propanol, and 0.5 ppm for methanol in the steam condensates.

4. RESULTS

Tracer tests were conducted for the four injection wells from 2000 to 2003. The results of three tests are shown in Table 1. The return of tracers was detected for each test, and then the flow paths (relation of injection points to feed points) were determined (Figure 2). The return curves were sufficiently smooth that the recoveries of tracers could be calculated (Figures 3, 5 and 6, and Table 1). Results from the individual tests are presented below.

4.1 Test for well MR-1

Water injection into well MR-1 has continued for 15 years (1988 to 2003) at injection rates ranging from 10 t/h to 130 t/h. The first two-phase tracer test was conducted to determine the flow paths from well MR-1. The mixed solution of 770 kg ethanol and 130 kg i-propanol was injected directly from metal barrels to the wellhead in eight minutes under negative pressure. Tracer returns were found in production wells M-1, M-5 and M-12, and smooth return curves were obtained for each (Figure 3). The detection of the tracer lasted more than two months, which shows that the alcohols were stable long enough for evaluation of the recoveries. The largest recovery in well M-12 showed the preferential flow toward it (Table 1).

Although the ethanol / i-propanol ratios of condensates taken from wells M-5 and M-12 were the same as the tracer's, the ratio of the samples from well M-1 was smaller (Figure 4). Being more volatile than i-propanol, some of the ethanol may have boiled off and escaped to a fracture disconnected from well M-1.

A second test for well MR-1 was conducted in 2003 with more tracer injected (3,200 kg of i-propanol). The returns were also found in well M-8 and M-15 in addition to wells M-1, M-5 and M-12 (Figure 2).

4.2 Tests for wells M-6 and M-13

Short-term injection studies including tracer tests were conducted on well M-6 for nine months and on well M-13 for a month. Well M-8 showed changes in the production rate, steam temperatures and NCG concentrations in the several months after the injection into well M-6, which indicated a breakthrough from well M-6 to well M-8. Non-condensable gas concentrations also showed evidence of flow paths from well M-6 to well M-13, although M-13 continued to produce dry steam during the injection.

The tracer n-propanol (1,560 kg) was injected into well M-6 with a pump in 20 minutes. The tracer was detected in wells M-8 and M-13 (Figures 2 and 5). The initial detection from well M-8 was after only 10 hours and the recovery was very large (73%; Table 1), indicating the high permeability between wells M-6 and M-8 consistent with the above phenomena. The duration of tracer detection was about a month and the total recovery was 82% as steam.

A test for well M-13 was conducted using a mixture of 710 kg methanol and 680 kg ethanol; this showed a return at well M-6 and hence a single flow path between wells M-6 and M-13.

4.3 Test for well M-14

The tracer injection into well M-14 was conducted during its drilling, using a drilling pipe which was set close to the main fracture. Well M-14 has been a production well and the aim of the test was to investigate production interference with the surrounding wells. Being located in the highest-temperature upflow zone, well M-14 and the two neighboring wells, M-7 and M-11, produce superheated steam.

A mixed tracer of 650 kg ethanol and 1,290 kg i-propanol flowed to wells M-7 and M-11 (Table 1, Figures 2, and 6). The initial detection was after 4 and 17 hours for well M-11 and M-7, respectively. The returns lasted for only two days and the recoveries were quite small (0.5%), which means the more than 99% of tracer was missing. It is possible that most of the tracer and injected water flowed downwards in the high steam-saturated region because of the difference in the densities of steam and water. The peak concentration of ethanol was detected earlier than that of i-propanol at well M-11 (Figure 6). The difference in their volatilities and the property of a two-phase flow in the high steam-saturated condition may have contributed to this phenomenon.

5. CONCLUSIONS

Alcohols (methanol, ethanol, n-propanol, and i-propanol) were used as two-phase tracers. It was shown that the alcohols were detectable for two months at temperatures up to 260°C in the Matsukawa field.

The return curves were as smooth as those obtained for liquid-phase tracers, and recoveries were calculated. The tracer velocities and recoveries showed preferential flow paths from the injection wells.

The mixed alcohol tracers showed behaviors consistent with boiling processes and two-phase flow patterns in the vapor-dominated reservoir. Mixed alcohol solutions have potential as two-phase tracers from which the boiling process of injected water can be deduced.

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REFERENCES

Adams, M. C. Vapor, Liquid, and Two-phase Tracers for Geothermal Systems.: *Proc. World Geothermal Congress*, 1995, p. 1875-1880.

Adams, M. C., Yamada, Y., Yagi, M., Kondo, T., and Wada, T.: Solubility of Methanol, Propanol, and SF_6 as High-temperature Tracers, *Proc. World Geothermal Congress*, 2000, p. 3015-3019.

Adams, M. C., Beall, J. J., Enedy, S. L., and Hirtz, P.: The Application of Halogenated Alkanes as Vapor-phase Tracers: a Field Test in the Southeast Geysers, *Transactions, Geothermal Resources Council*, 1991a, Vol. 15, p. 457-463.

Adams, M. C., Moore, J. N., and Hirtz, P.: Preliminary Assessment of Halogenated Alkanes as Vapor-phase Tracers, *Proceedings, 16th Workshop on Geothermal Reservoir Engineering, Stanford University*, 1991b, p. 23-25.

Adams, M. C., Beall, J. J., Enedy, S. L., Hirtz, P. N. Kilbourn, P., Koenig, B. A., Kunzman, R., and Smith, J. L. B.: Hydrofluorocarbons as Geothermal Vapor-phase Tracers, *Geothermics*, 2001, Vol. 30, p. 747-775.

Beall, J. J., Adams, M. C., and Hirtz, P. N.: R-13 Tracing of Injection in The Geysers, *Transactions, Geothermal Resources Council*, 1994, Vol. 18, p. 151-159.

Beall, J. J., Adams, M. C., and Hirtz, P. N.: Evaluation of R-134A as an Injection Water Tracer in the Southeast Geysers, *Transactions, Geothermal Resources Council*, 1998, Vol. 22, p. 20-23.

Voge, E., Koenig, B., Smith, J. L. B., and Enedy, S.: Initial Findings of The Geysers Unit 18 Cooperative Injection Project, *Transactions, Geothermal Resources Council*, 1994, Vol. 18, pp. 353-357.

Glover, R. B. and Kim, J. P.: SF_6 - A New Nonradioactive Geothermal Tracer, *Proc. 15th New Zealand Geothermal Workshop*, 1993, Vol, 15, p. 125-132.

Lovelock, B. G.: Steam Flow Measurement Using Alcohol Tracers. *Geothermics*, 2001, Vol. 30, p. 641-654.

Lovelock, B. G. and Stowell, A.: Mass Flow Measurement by Alcohol Tracer Dilution, *Proc. World Geothermal Congress*, 2000, pp. 2701-2706.

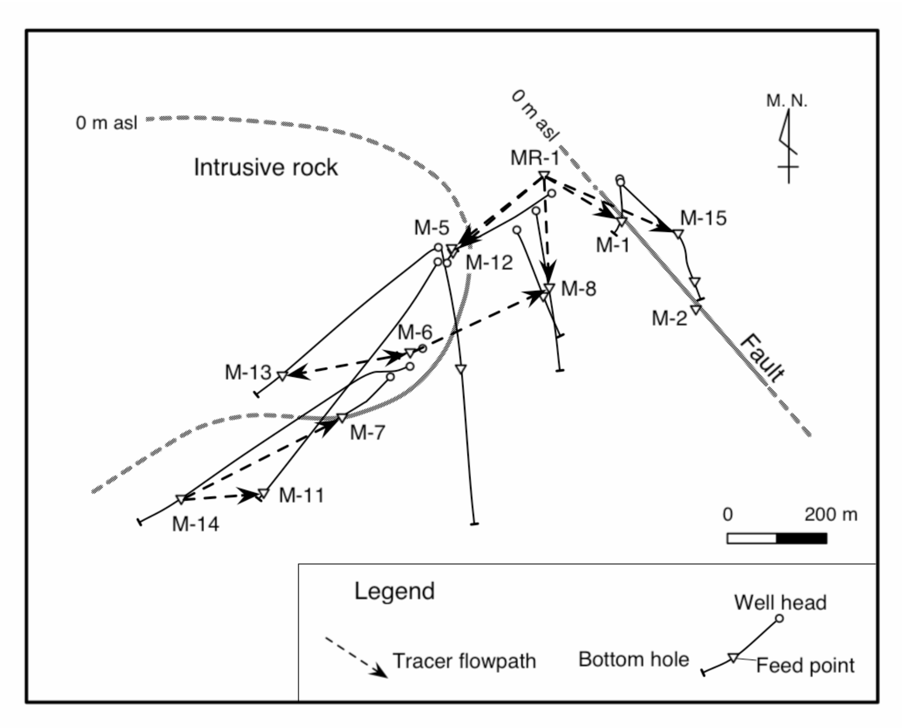

Figure 2. Well locations and flow paths of tracers.

Table 1. Results of tracer tests at the Matsukawa geothermal field.

Injection well	Injection date / Tracer	Production well	Recovery (%)		Initial detection time (h)	Tracer velocity (m/h)
MR-1	6-Aug-00 ethanol: 770 kg + i-propanol: 130 kg	M-1	ethanol	1.5	30	7
			i-propanol	2.5		
		M-5	ethanol	6.5	145	3
			i-propanol	3.3		
		M-12	ethanol	24	121	3
			i-propanol	17		
M-6	12-Sep-00 n-propanol: 1,530 kg	M-8	n-propanol	73	10	39
		M-13	n-propanol	9.1	49	5
M-14	18-May-01 ethanol: 650 kg + i-propanol: 1,290 kg	M-7	ethanol	-	-	-
			i-propanol	0.08	17	32
		M-11	ethanol	0.30	4	61
			i-propanol	0.24		

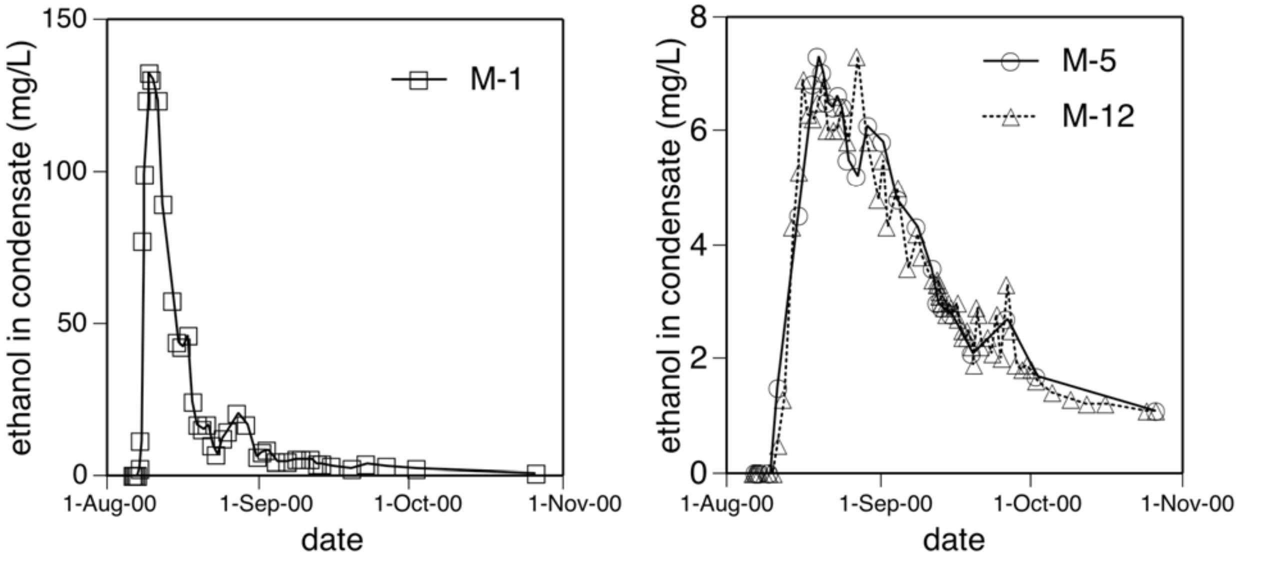

Figure 3. Return curves obtained by the MR-1 tracer test. The returns started in 30 hours for well M-1 and in over 120 hours for wells M-5 and M-12, and continued for more than two months.

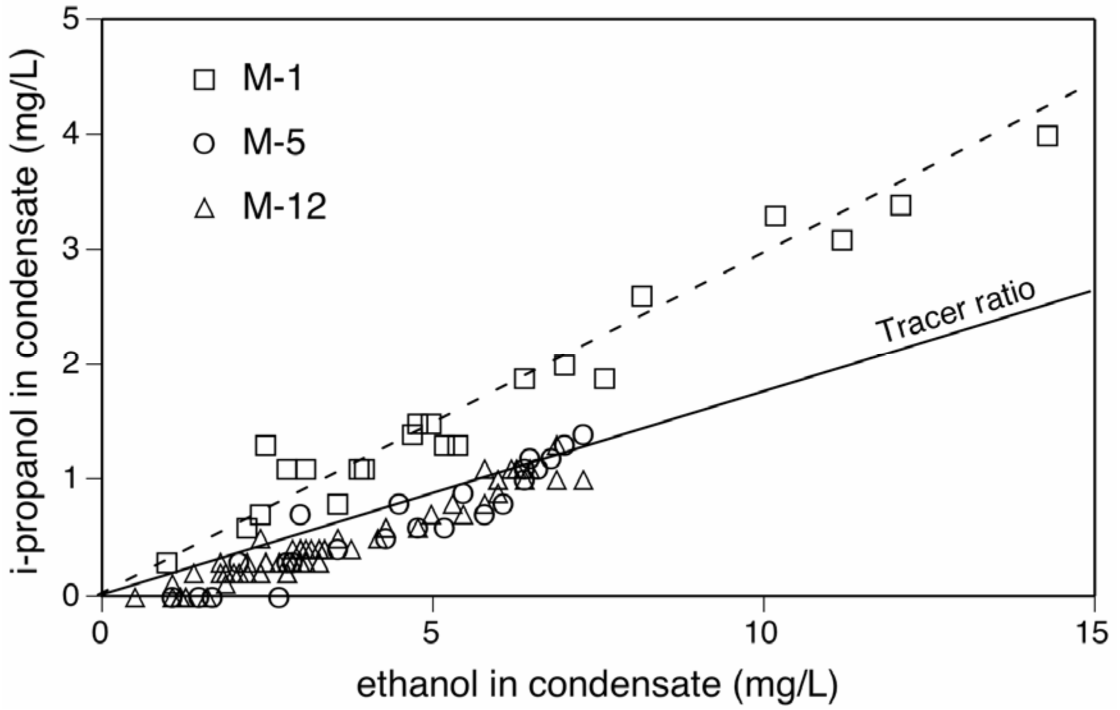

Figure 4. Relationship between ethanol and i-propanol concentrations of wells M-1, M-5 and M-12. The correlation line of well M-1 (dotted line) differs from those of wells M-5, M-12 and the tracer (solid line). Well M-1 is depleted in ethanol which is more volatile than i-propanol.

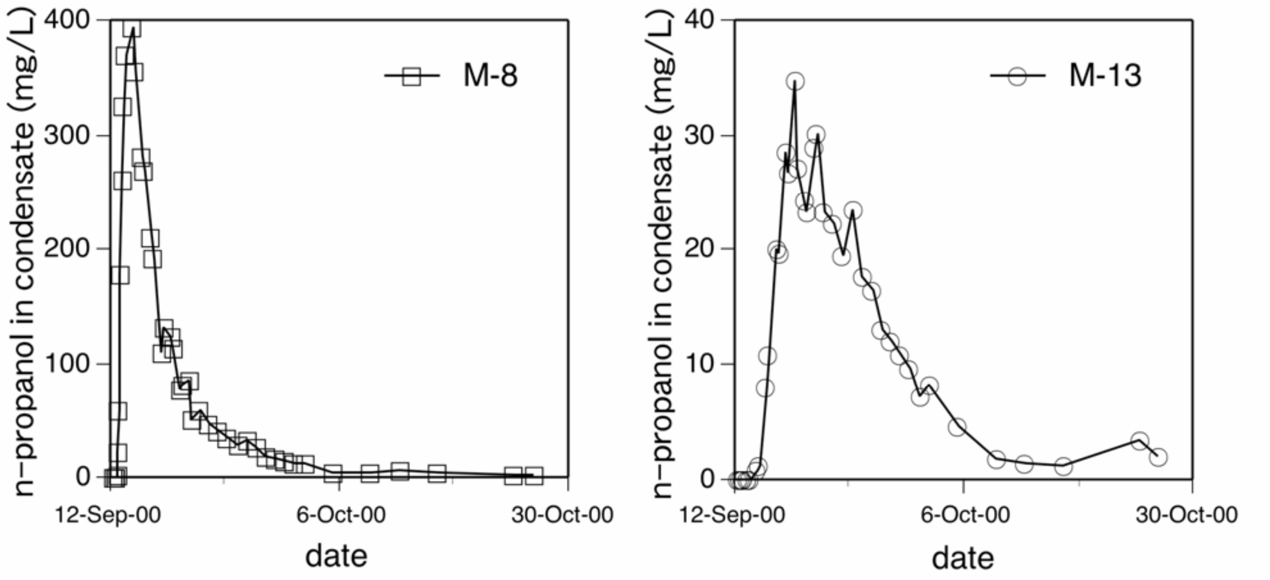

Figure 5. Return curves obtained by the M-6 tracer test. It shows the quick return in 10 hours at well M-8. The returns lasted for more than a month.

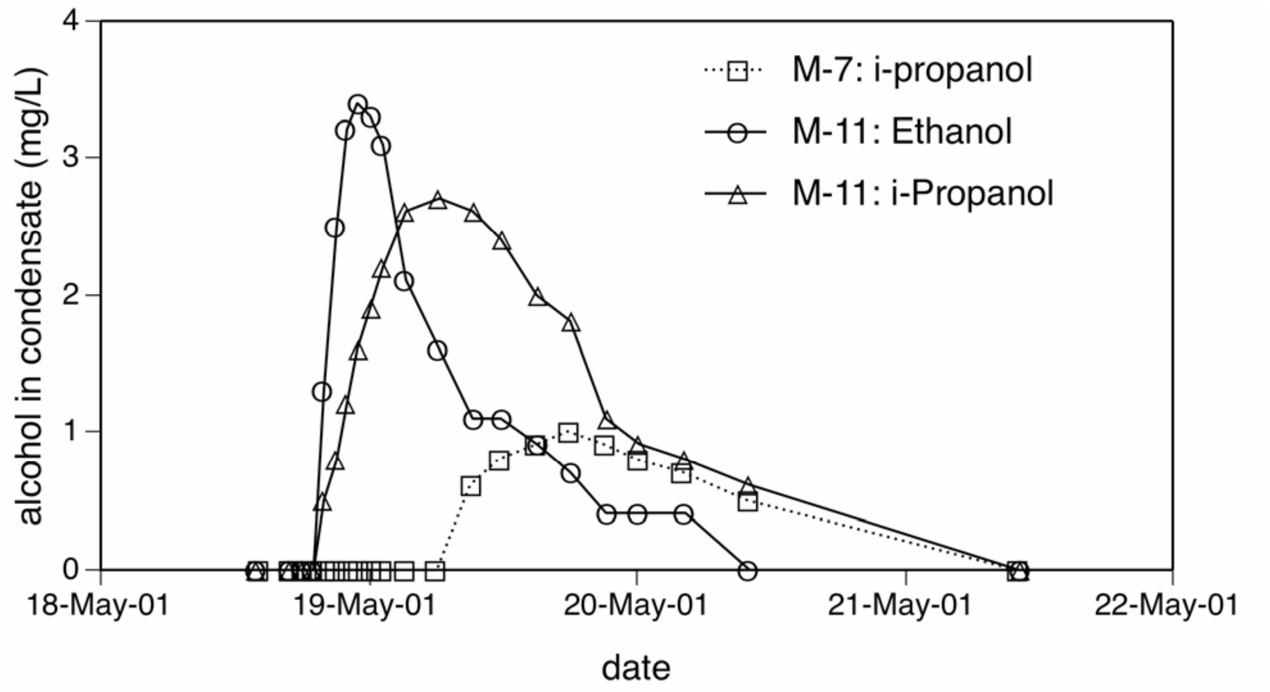

Figure 6. Return curves obtained by the M-14 tracer test in the high-temperature upflow zone, showing quick and short term returns within two days. The recoveries are much smaller than those of other tests (see Table 1). The different peak times of ethanol and i-propanol for well M-11 seem to result from the difference in the volatilities of them and the property of a two-phase flow in the high steam-saturated condition.