The Use of Butanols as Tracers at the Coso Geothermal Field

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Geothermal tracers, alcohol tracers, geothermal energy, reservoir management, Coso geothermal field

ABSTRACT

A tracer test was conducted within the east flank compartment at the Coso geothermal field using naphthalene sulfonate tracers in combination with methanol and three isomers of butanol (n-butanol, 2-butanol and isobutanol). Methanol and two of the three butanol isomers (n-butanol and 2-butanol) were measured in production wells and in concentrations much greater than their detection limits. The east flank compartment has temperatures at depth exceeding 275°C. In spite of significant thermal degradation, the isomers of butanol proved to be useful tracers under the thermally demanding conditions at the Coso geothermal field.

Introduction

Compounds from the family of naphthalene sulfonates have gained wide acceptance for use as tracers in liquid-dominated geothermal reservoirs (Rose et al., 2001). Only eight isomers of the naphthalene sulfonates are available in bulk, however, and more tracers are needed when tracing injection fluids in large reservoirs containing many injection wells. For any compounds to be useful as geothermal tracers they must be thermally stable, detectable in very low concentrations, affordable in bulk and environmentally benign.

Recent work has shown that short chain aliphatic alcohols meet these requirements—especially for tracing two-phase flow in depleted reservoirs (Adams et al., 2004). They are polar molecules, allowing them to be soluble in water and providing for both easy injection and sampling. They have a vapor-liquid equilibrium coefficient that is similar to water, permitting the alcohol to follow the injected water more closely by partitioning between the liquid and steam phases. And, they are sufficiently stable to survive for extended periods of time at geothermal temperatures. In addition, they are nontoxic and pose no environmental hazards. Among the short-chain aliphatic alcohols, ethanol and n-propanol have been successfully used as geothermal tracers (Fukuda et al., 2005; Mella et al., 2006a,b). This paper presents the first reported use of three butanol isomers (n-butanol, 2-butanol, and isobutanol) and methanol as tracers in a geothermal reservoir.

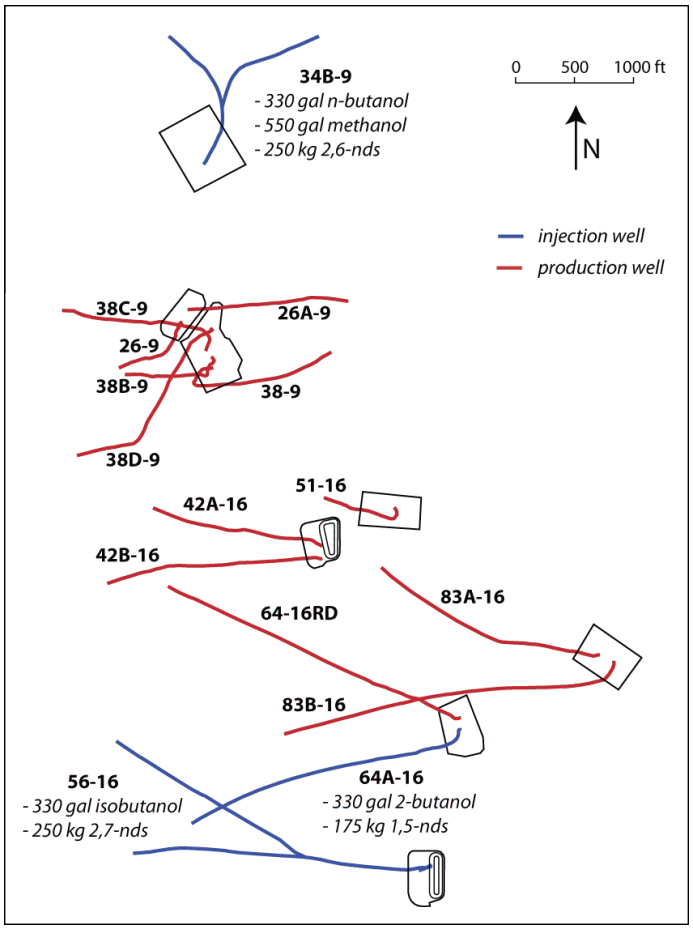

Figure 1. Plan view of the east compartment of the Coso geothermal field showing the relevant injection wells (in blue) and production wells (in red).

The Coso Geothermal Field

The Coso geothermal field is located in the Mojave Desert, east of the Sierra Nevada Mountains within the Naval Air Weapons Station, China Lake, California (Monastero, 2002). With an installed capacity of approximately 270 MWe, it is operated by Coso Operating Company LLC and has been in full operation since 1989. The field is compartmentalized into three major zones that have little interaction with each other. The focus of this paper is the eastern compartment of the Coso field, which is shown in Figure 1.

The Thermal Stability and Detectability of Butanol Tracers

The thermal stabilities of the short-chain aliphatic alcohols increase in inverse proportion to the number of atoms in the carbon backbone: butanol < propanol < ethanol < methanol (Adams et al., 2004). Likewise, their detection limits increase in the same order, making butanol more detectable but less thermally stable than methanol.

For the tracer test at Coso, the three butanols, n-butanol, 2-butanol, and iso-butanol (see Figure 2) were used in addition to methanol.

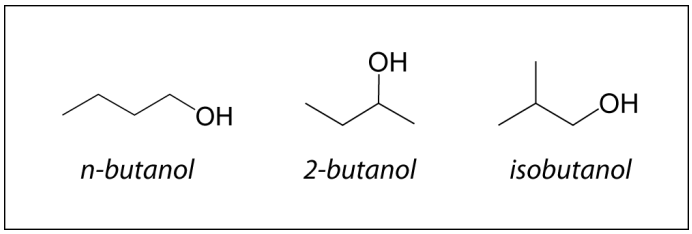

Figure 2. Chemical structures of the butanols.

Among the butanols, thermal stabilities increase according to the sequence: tert-butanol < 2-butanol < iso-butanol < n-butanol. Adams claims that n-butanol can be used as a purely non-reactive (i.e. non-decaying) tracer only at temperatures less than 250ºC (Adams et al, 2004). The reservoir temperature within the Coso east-flank compartment exceeds 275 ºC, significantly hotter than the maximum use temperature recommended by Adams. It was therefore expected that the butanols would behave as reactive tracers and experience significant thermal decay, but that enough of each parent compound would remain to allow for detection within the production wells and thereby demonstrate interwell connectivity (where it exists). As a precaution, the very thermally stable methanol was co-injected as a conservative tracer with n-butanol.

The Tracer Test

On March 2, 2012, 330 gal of n-butanol, 550 gal of methanol and 250 kg of 2,6-naphthalene disulfonate (2,6-nds) were injected into the northern-most injection well 34B-9 (see Figure 1). On March 4, 330 gal of 2-butanol and 175 kg of 1,5-naphthalene disulfonate were injected into an injection well in the southern part of the east flank compartment, 64A-16. On March 5, 330 gal of iso-butanol and 250 kg of 2,7-naphthalene disulfonate (2,7-nds) were injected into another southern injection well, 56-16. The fluids from the surrounding production wells were sampled over the subsequent several weeks and analyzed for the alcohol and naphthalene sulfonate tracers.

The methanol and butanol tracers were sampled from a side stream of condensed steam. Given the vapor-liquid equilibrium partitioning between the steam and liquid phases not only within the reservoir but within the wellbore, care must be taken to sample and analyze for methanol and the butanols in both the condensed steam and the brine. In a previous test involving n-propanol within the east flank of the Coso geothermal field, however, very low concentrations of n-propanol were measured in the brine phase. In the current study, the alcohol tracers were measured only in the condensed steam.

Methanol and the butanols were analyzed using solid-phase micro-extraction (SPME) followed by GC/MS as described previously (Mella et al., 2006a,b). Using this method, the detection limits for the butanols were approximately 1 part-per-billion (ppb). In contrast, the detection limit for methanol was approximately 50 ppb.

Returns of Tracers to the Northern Production Wells

The active wells closest to the 34B-9 injection well are located on the 26-9 pad (wells 26-9 and 26A-9) on the 38-9 pad (wells 38-9, 38B-9, 38C-9, and 38D-9; see Figure 1).

Producer 38B-9

In well 38B-9, the alcohol tracer methanol and the liquid phase tracer 2,6-nds were both observed to arrive at approximately the same time but in relatively low concentrations (see Figure 3).

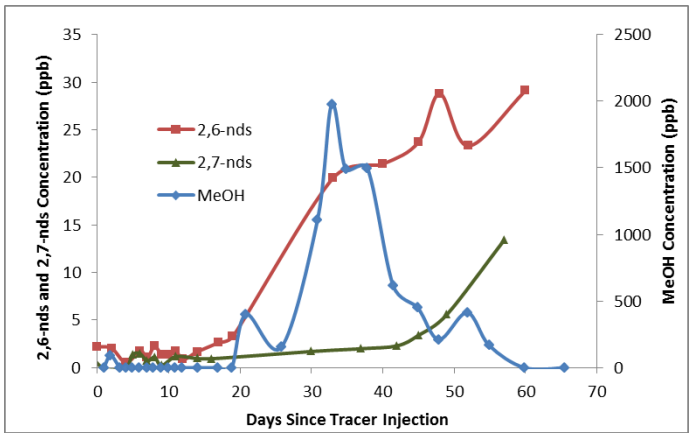

Figure 3. Plots of methanol and 2,6-nds that had been injected simultaneously in well 34B-9 and produced in well 38B-9. Note that no n-butanol was observed in this well, since it had likely thermally degraded below its detection limit.

Producer 38C-9

In well 38C-9, methanol, n-butanol, and 2,6-nds were observed, although the low concentrations of n-butanol relative to the thermally stable methanol indicate that n-butanol was very thermally degraded (see Figure 4).

Producer 38D-9

Even less methanol was observed in 38D-9 than had been observed in 38B-9 (see Figure 5). Likewise, as in 38B-9, any

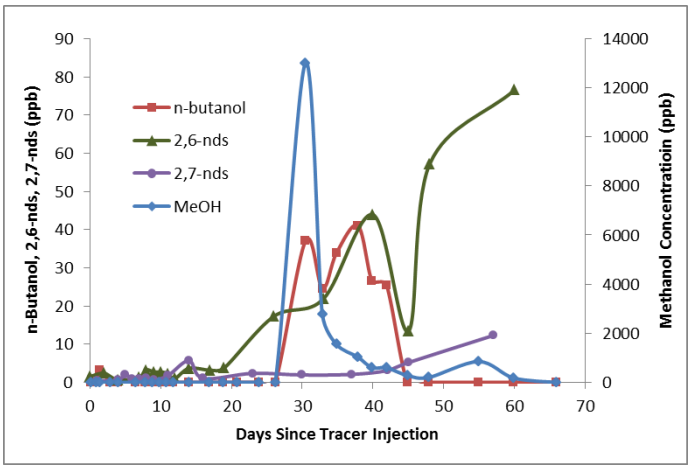

Figure 4. Plots of methanol and n-butanol that had been injected simultaneously in well 34B-9 and produced in well 38C-9. Note that 2,6-nds was also observed in this well, arriving at approximately the same time as the alcohol tracers but peaking later.

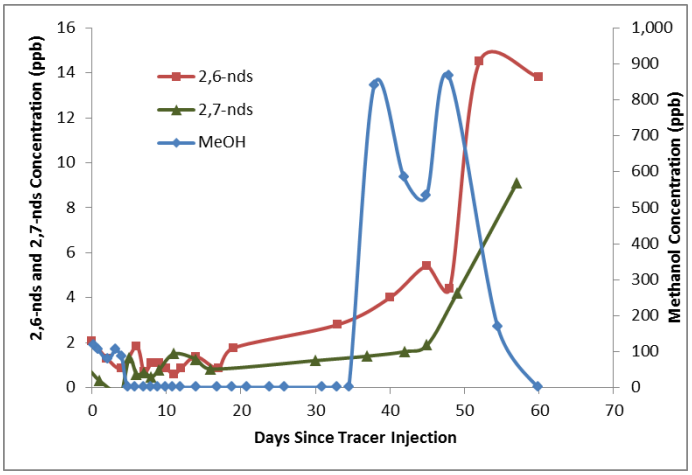

Figure 5. Plots of methanol and two naphthalene sulfonate tracers observed in well 38D-9. Both methanol and 2,6-nds had been injected in 34B-9, with the methanol arriving slightly ahead of the 2,6-nds.

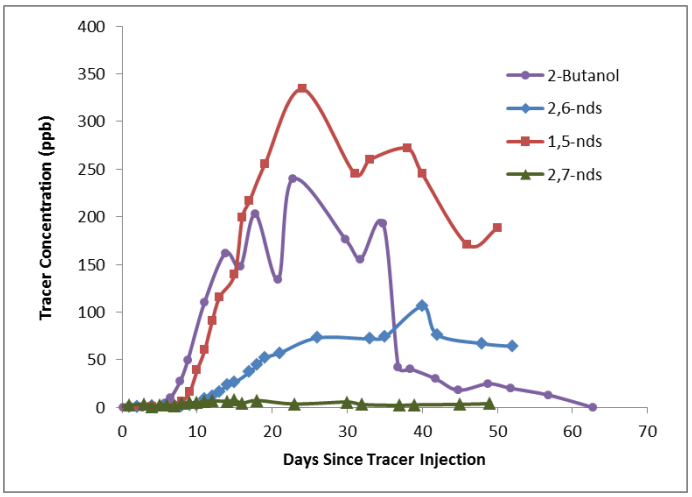

Figure 6. A plot of tracers introduced into 64A-16 (2-butanol and 1,5-nds) and produced in well 83B-16. 2-butanol, a two-phase tracer, slightly preceded the arrival of the liquid-phase tracer 1,5-nds.

n-butanol that might have been observed had already decayed below its detection limit before arriving in this producer. The two-phase tracer methanol arrived slightly ahead of the liquid phase tracer 2,6-nds, which had been injected simultaneously with methanol.

Returns of Tracers to the Southern Production Wells

Producer 83B-16

Shown in Figure 6 are the returns of tracer to the well 83B-16, the southern-most production well in the east flank compartment. The two-phase tracer 2-butanol and the liquid phase tracer 1,5-nds were injected simultaneously into 64A-16 and the two tracers track each other quite closely in their flow to 83B-16, with the alcohol tracer slightly leading the liquid tracer as expected. The 2-butanol signal drops more quickly than that of 1,5-nds, due to the thermal decay of the 2-butanol.

Producer 83A-16

Shown in Figure 6 are the returns of tracer to the well 83A-16. First to arrive were tracers introduced into 64A-16 (2-butanol and 1,5-nds). These two tracers track each other quite closely, with the 2-phase tracer 2-butanol slightly preceding the liquid phase tracer, 1,5-nds.

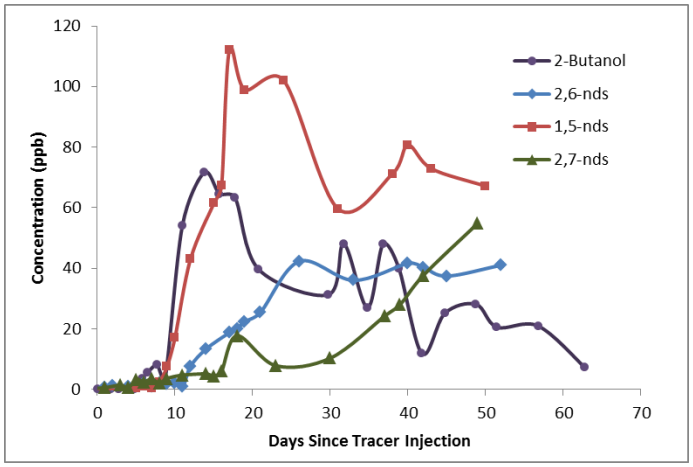

Figure 7. A plot of tracers produced at well 83A-16. First to arrive were tracers introduced into 64A-16 (2-butanol and 1,5-nds) followed by the tracer 2,6-nds, which had been injected into 34B-9 on the northern end of the east flank compartment. The last to arrive was 2,7-nds, which had been co-injected with two-phase tracer isobutanol into well 56-16.

Producer 64-16RD

Shown in Figure 8 are the tracer returns to 64-16RD, another major production well in the southern part of the east flank compartment. First to arrive were tracers introduced into 64A-16 (2-butanol and 1,5-nds), although the expected order was reversed with 1,5-nds arriving slightly before 2-butanol. The strongest returns were of tracer 2,7-nds (injected into 56-16), with modest returns of 2,6-nds (injected into 34B-9). Although isobutanol had been co-injected with 2,7-nds into 56-16, no isobutanol was observed in 64-16RD, possibly due to its poor thermal stability.

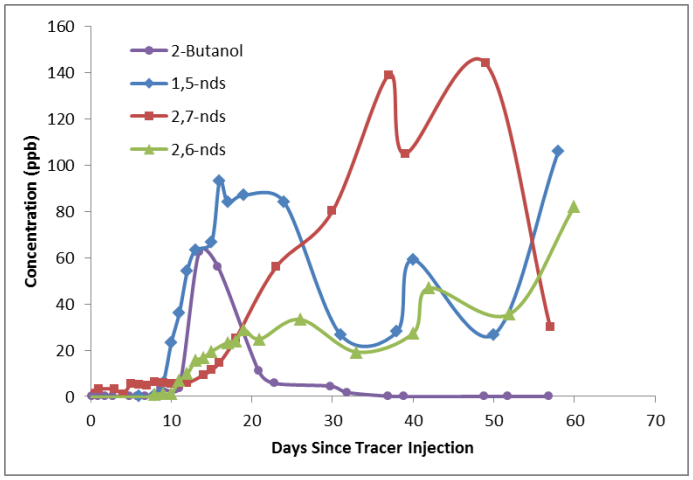

Figure 8. A plot of tracers produced at well 64-16RD. First to arrive were tracers introduced into 64A-16 (2-butanol and 1,5-nds), followed by the tracer 2,6-nds, which had been injected into 34B-9 and 2,7-nds, which had been co-injected with the two-phase tracer isobutanol into well 56-16.

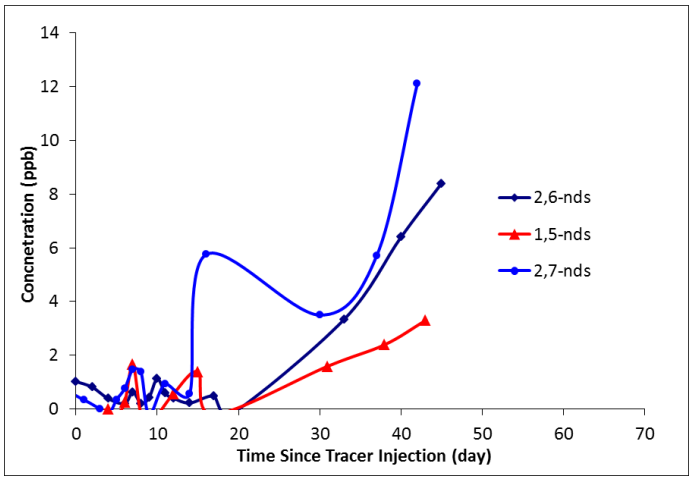

Figure 9. A plot of tracers produced at well 51-16. None of the alcohol tracers were observed in this well.

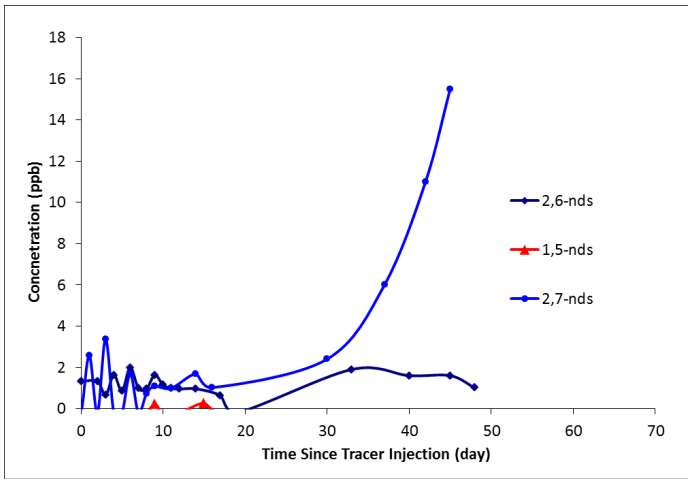

Figure 10. A plot of tracers produced at well 42B-16. None of the alcohol tracers were observed in this well.

Returns of Tracers to the Central Wells

This group, which includes the producers 51-16, 42A-16, and 42B-16, showed the least amount of tracer production of any of the east flank wells. At the submission date of this paper, none of the alcohol tracers were observed and only low concentrations of the naphthalene sulfonates were produced.

Shown in Figure 9 are the plots of each of the three naphthalene sulfonate tracers produced at well 51-16 and in Figure 10 the production of these three tracers in 42B-16. Only traces of the naphthalene sulfonate tracers were observed in 42A-16 (plot not shown).

Summary of Tracer Returns

Figure 11 shows the tracer flow patterns between the various injection and production wells. Each arrow color represents the particular combination of alcohol and naphthalene sulfonate tracers injected into each injector, with the thickness of the arrow approximately proportional to the concentration of tracers produced.

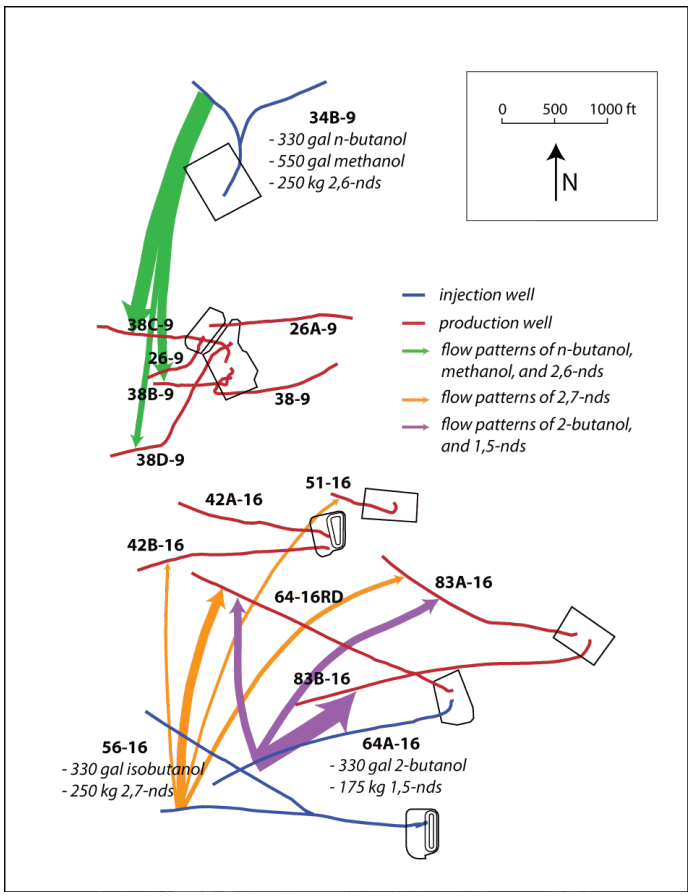

Figure 11. A plan view of the east flank compartment showing wellbore deviations and the tracer flow patterns between injectors and producers. The thickness of each arrow is approximately proportion to the concentration of tracer produced.

Shown in Table 1 is a listing of the percentage of each tracer returned 52 days after injection. These percentages were obtained from a numerical integration of the concentration vs. time plots

multiplied by the average flow rate of each production well and divided by the mass of each tracer injected.

Table 1. Tracer Returning to the East Flank Production Wells 52 Days after Tracer Injection.

	Injection Well (tracer designation)						
Production Well	**34B-9 (meOH)**	**34B-9 (n-buOH)**	**64A-16 (2-buOH)**	**56-16 (iso-buOH)**	**34B-9 (2,6-nds)**	**64A-16 (1,5-nds)**	**56-16 (2,7-nds)**
26-9	0.65%	0.01%	0.00%	0.00%	0.01%	0.00%	0.00%
26A-9	0.00%	0.00%	0.00%	0.00%	0.02%	0.00%	0.01%
38-9	0.00%	0.00%	0.00%	0.00%	0.05%	0.00%	0.05%
38B-9	2.34%	0.01%	0.01%	0.00%	0.34%	0.00%	0.04%
38C-9	8.82%	0.12%	0.00%	0.00%	0.06%	0.01%	0.04%
38D-9	0.76%	0.00%	0.00%	0.00%	0.06%	0.00%	0.03%
42A-16	0.01%	0.00%	0.00%	0.00%	0.05%	0.00%	0.03%
42B-16	0.00%	0.00%	0.00%	0.00%	0.02%	0.00%	0.06%
51-16	0.00%	0.00%	0.00%	0.00%	0.03%	0.02%	0.06%
64-16RD	0.00%	0.00%	0.01%	0.00%	0.20%	0.51%	0.51%
83A-16	0.00%	0.00%	0.12%	0.00%	0.36%	1.14%	0.21%
83B-16	0.01%	0.01%	0.64%	0.00%	0.92%	4.54%	0.07%
Total	**12.60%**	**0.15%**	**0.79%**	**0.00%**	**2.13%**	**6.24%**	**1.12%**

It is evident that the percentage of n-butanol returned was much less than the percentage returned of the thermally stable methanol, although these two tracers were co-injected into the same well. This reflects the significant thermal degradation of the n-butanol at the high temperatures within the east flank compartment (>275ºC). In spite of thermal degradation, sufficient concentrations of n-butanol were nevertheless observed for the purpose of demonstrating interwell connectivity. With the exception of methanol, the percentage return of the alcohol tracers was much less than the returns of the naphthalene sulfonate tracers.

Note that the thermally stable 2-phase tracer methanol returned to the production wells on the 38-9 pad (38B-9, 38C-9, and 38D-9) in higher percentages (2.34%, 8.82%, and 0.76%, respectively) and in different distributions than the thermally stable naphthalene sulfonate tracer 2,6-nds (0.34%, 0.06%, and 0.06%, respectively) to the same wells. These differences reflect the higher percentage of steam produced in these wells relative to brine.

Summary and Conclusions

A tracer test was conducted at the Coso geothermal field using naphthalene sulfonate tracers in combination with methanol and three isomers of butanol, representing the first time that methanol and the butanols have ever been used as geothermal tracers. Two of the three butanol isomers (n-butanol and 2-butanol) were measured in neighboring production wells and in concentrations much greater than their detection limits. The third butanol (isobutanol) was not detected. In most instances, the alcohol tracers tracked closely the flow of the co-injected liquid-phase naphthalene sulfonate tracers, with first arrivals generally slightly in advance of them. In spite of the very challenging thermal conditions, the butanols were both sufficiently stable and detectable to serve as useful tracers for tracing the flow of injected brine within the hot east flank compartment of the Coso geothermal field. Laboratory studies continue to characterize the thermal-decay kinetics of the butanols and to develop an improved method for the analysis of methanol.

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