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Tracer Testing at Los Humeros, Mexico, High-Enthalpy Geothermal Field

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ABSTRACT

We performed a tracer study in the high-enthalpy Los Humeros geothermal reservoir to assess the effects of produced-brine injection in the central part of the field. The reservoir is emplaced in fractured volcanic formations. A high-temperature, liquid-phase tracer, 2,6 naphtalene disulfonate, was used. Our results revealed that injection in well H-13 recharges the feeding zones of the nine monitored producing wells. Our results also indicate there is negligible risk of thermal interference in the observed wells at the injection rates of this study. The observed small aggregated tracer recovery suggests that most of the injected fluid, perhaps up to about 99%, flows to the deep reservoir, recharging it and enhancing its economic life. In this field the tracer residence curves present unusual patterns, as revealed in previous and the present study. We investigated the causes of these unusual patterns by measuring, for each well, the electric conductivity of the samples. Then we found a linear correlation between the mean electric conductivity of the samples with the average liquid fraction in the corresponding discharge. On this basis we concluded the main cause of the observed unusual patterns is that each production well monitored probably has at least two feeding zones with differing enthalpies.

1. INTRODUCTION

Los Humeros geothermal field sits atop of a volcanic caldera. It is a high-enthalpy geothermal resource emplaced in fractured volcanic formations.

At the time of this study the Mexican Comisión Federal de Electricidad (CFE), owner and operator of the field, was injecting about 4.2 kg/s of separated brine, produced in different parts of the field, in well H-13. The destination of the injected fluids as well as their likely capacity to produce unwanted thermal interference with producing wells is of considerable economic interest for CFE.

To investigate these questions teams of the Instituto de Investigaciones Eléctricas (IIE) and CFE jointly designed, implemented and analyzed the results of the study described in this paper.

2. MATERIALS AND METHOD

Nine production wells in the area of interest (Fig. 1) were selected for this study. Their names, distances to the injector H-13 and respective discharge quality are shown in Table 1.

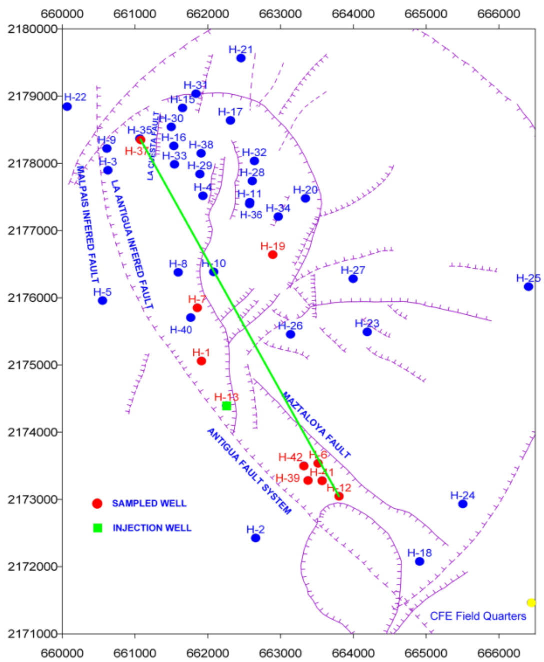

Figure 1: Location of the wells

Table 1: Well names, their distances to the injector and mean discharge quality

Pozo	Distance to H-13 (m)	Mean discharge quality
H-01	748	0.55
H-06	1,523	0.91
H-07	1,509	0.92
H-12	2,050	0.94
H-19	2,334	0.94
H-39	1,579	0.85
H-41	1,724	0.95
H-42	1,391	0.88
H-37	4,125	0.62

Figure 2 presents a vertical section between wells H-37D and H-12, showing the spatial relationships between the wells designated by CFE for this study.

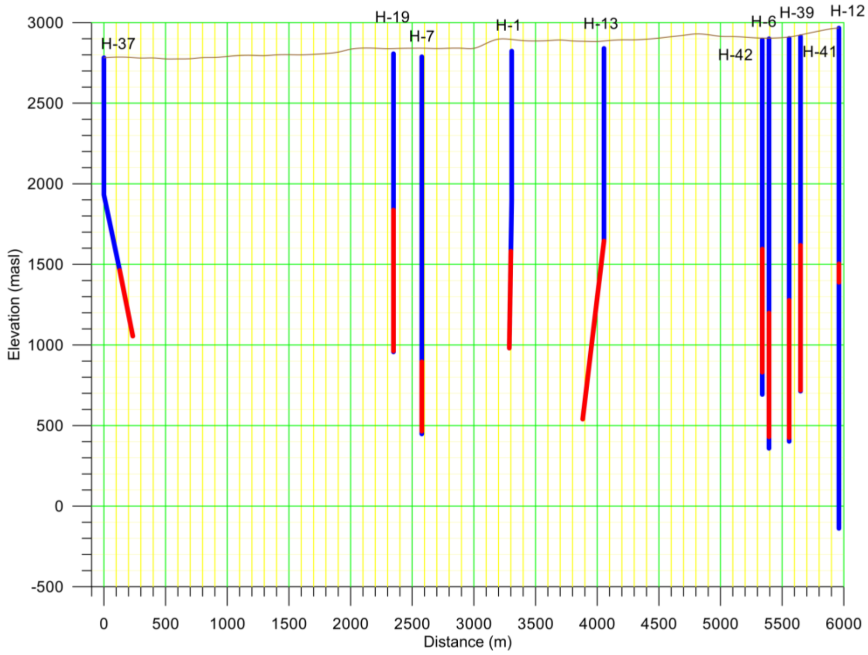

Figure 2: Spatial relationships between the wells

We chose 2,6 naphthalene disulphonate (nds) as our liquid-phase tracer considering its high-temperature thermal stability, low detection limit, negligible risk to the environment, simple logistics, commercial availability and affordable price, (e.g., Rose et al. 2001, 2002). Its analysis is implemented using liquid chromatography (HPLC), by UV florescence. With this method the detection limit is approximately 100 ppt.

Recovery curves were computed numerically integrating the product of the liquid flowrate times the concentration of the residence curves over the observation period:

$$m_j(t) = \int_0^t W_j(s).c_j(s)ds \qquad (1)$$

where $m_j(t)$ is the tracer mass recovered from well j since the injection ($t = 0$) until time t; $W_j(t)$ is the instantaneous mass flow of well j, and $c_j(t)$ is the instantaneous tracer concentration. The total tracer mass recovered from all wells is thus

$$m_R = \sum_j m_j \qquad (2)$$

We injected 300 kg of 2,6 nds dissolved in 1,500 *l* of injection brine, in well H-13. The injection operation lasted 18 minutes. Sampling of the participating wells, including H-13 started 4 hours later. For convenience the wells were sampled with diminishing frequency, a standard procedure in this kind of tracer test.

During a previous study in this field (Iglesias et al., 2007) the liquid-tracer residendence curves presented unusual patterns. We suspected these anomalous patterns were related to the existence of multiple feeds, of different enthalpy, in the wells. To test this hypothesis, in the present study we measured brine conductivity in each liquid sample.

3. RESULTS AND DISCUSSION

3.1 Hydraulic connectivity in the reservoir

Figures 3-5 present the tracer residence curves and the corresponding recovery curves for each monitored production well. As shown in these figures, the sampling period covered 272 days. Eighty samples were taken in each well.

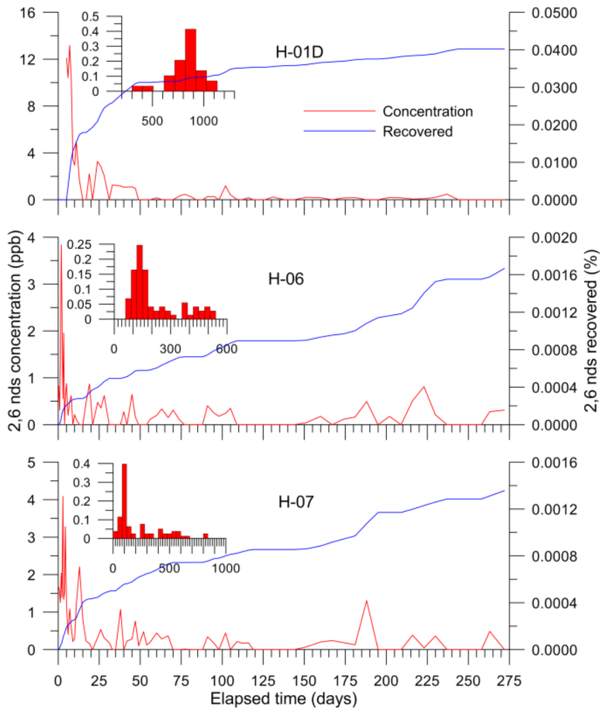

Figure 3: Residence and recovery curves of wells H-01, H-06 and H-07

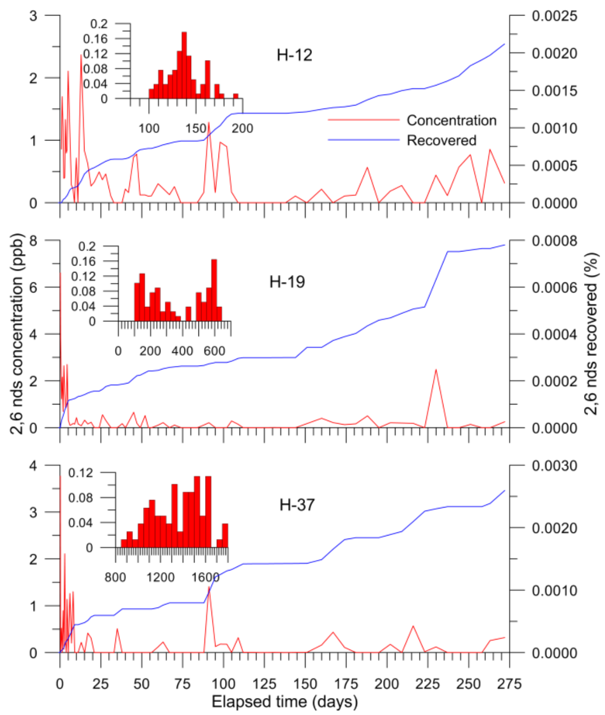

Figure 4: Residence and recovery curves of wells H-12, H-19 and H-37

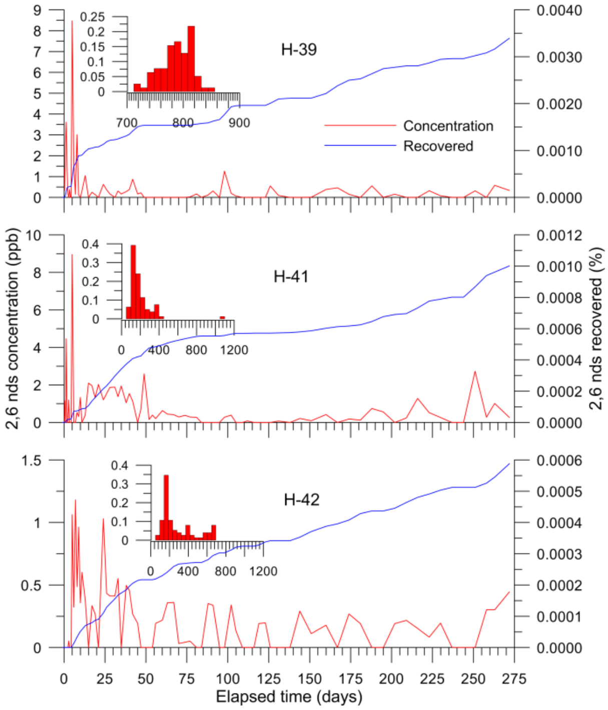

Figure 5: Residence and recovery curves of wells H-39, H-41 and H-42

The residence curves of the production wells were corrected for tracer recirculation, evidenced by its detection in the injector H-13D (Fig. 6). The correction was achieved using the deconvolution algorithm developed by Shook and Forsmann (2005). To apply this algorithm we approximated the tracer injection by an instantaneous pulse, considering that its 18 minutes duration was much shorter than the observation period (272 days). For all the wells the recirculation correction resulted negligible during the observation period.

As shown in Figs. 3-5, the tracer was detected in all nine monitored wells. This demonstrated that injection in well H-13 recharges the nine wells monitored in this study.

The short arrival times of the tracer to the production wells suggests the existence of an areally extensive subhorizontal permeability distribution within the studied area. This permeability distribution is not obviously associated with the known distribution of faults in Los Humeros; it might be associated with contacts among geological formations.

3.2 Fraction of tracer recovered in the production wells

Note that, with the exception of well H-01D, the recovery curves in Figs, 2-4 were monotonously increasing during the sampling period, indicating that the tracer was still arriving to the wells when sampling concluded. In well H-01D, the closest to the injector, the recovery curve reached a final plateau and tracer arrival seems to be essentially completed.

As in this case, occasions in which sampling is terminated before arrival of the tracer is completed in the production wells, are frequent. In those cases one may attempt to estimate the mass of tracer that would have been recovered in each well by extrapolating the tendency of the late part of the corresponding residence curve (e.g., Shook and Forsmann, 2005). Unfortunately, in the present case we were unable to use that method due to the unusual patterns presented by the residence curves: their succession of peaks and valleys during the observation period precludes discerning the late tendencies in them. Therefore, the recovery percentages computed for the observation period represent just a lower limit of the expected recovery for these wells.

Table 2 presents the percentage of tracer recovery for all wells during the sampling period. As shown, the total tracer recovery during the study (0.0537%) is very small. Remember however that tracer was still arriving to all production wells, except H-01D, when sampling was terminated. It´s worth mentioning however that the registered total tracer recovery is consistent with a previous result (0.131%) registered in the northern part of this field (Iglesias et al, 2007), over a smaller area and a shorter observation period (205 days). In that case the liquid-phase tracer completed its arrival in eight of the nine monitored wells.

In order to check for tracer recirculation we sampled the injection well simultaneously with the other wells. The corresponding results are presented in Fig.5. The total recirculated tracer amounted to 0.0076 % of the injected tracer, which represents 14.15% of the total recovered tracer in the production wells. Therefore significant tracer recycling occurred during the sampling period.

The observed total recovery of producing wells (Table 2) is small and comparable to a previous result (0.131%) obtained in the Northern part of this field (Iglesias et. al., 2007) over a smaller area and a shorter period (205 days); in that case tracer recovery reached completion in all the wells but one. In the current study most wells did not reach recovery completion; only H-01D did. Thus, in principle one can hardly conclude anything about what would have been the total recovery if sampling had continued until all wells reached recovery completion. However, in previous tracer studies on fractured geothermal fields, including this one (Iglesias et al, 2007; 2010), we found that, in general, tracer recovery diminishes rapidly with distance to the injector well. In this case H-01D, the closest well to the injector, recovered about 75% of the recorded total. This and Fig. 6 suggests a similar pattern to that found in previous studies prevails in this one.

Table 2: Tracer recoveries

Well	Distance to H-13 (m)	Tracer recovery (%)
H-01	748	0.0402
H-06	1,523	0.0017
H-07	1,509	0.0014
H-12	2,050	0.0021
H-19	2,334	0.0008
H-39	1,579	0.0026
H-41	1,724	0.0034
H-42	1,391	0.0010
H-37	4,125	0.0006
Total recovery		**0.0537**

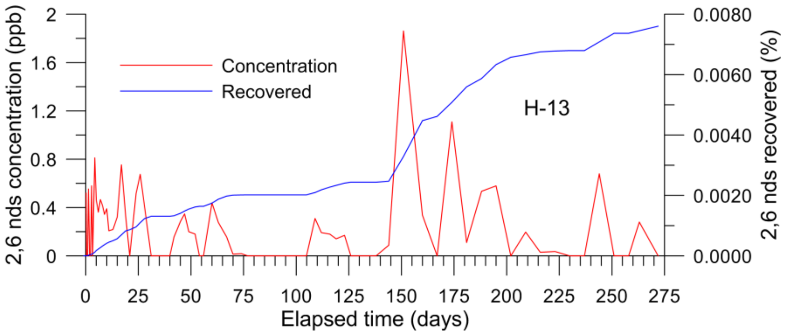

Figure 6: Results for the injection well

Assuming that to be the case, it is reasonable to expect that, once completed in all the wells, total tracer recovery would be of the same or similar order of magnitude as the recovery found for well H-01D. Furthermore, it seems very likely that part of the injected tracer would be produced by wells not monitored in this study, as suggested by the detection of the tracer in wells H-19 and H-37 located respectively at 2,334 and 4,125 m from the injector well. Even so, the small magnitude of the recovery indicates that most of the injected fluid is dispersed in the reservoir. A reasonable scenario for this to happen is that most of the injected brine, being colder and denser than the reservoir fluid, flows downwards to depths greater than those corresponding to the feeding zones of the wells, recharging the deep reservoir and enhancing its economic life.

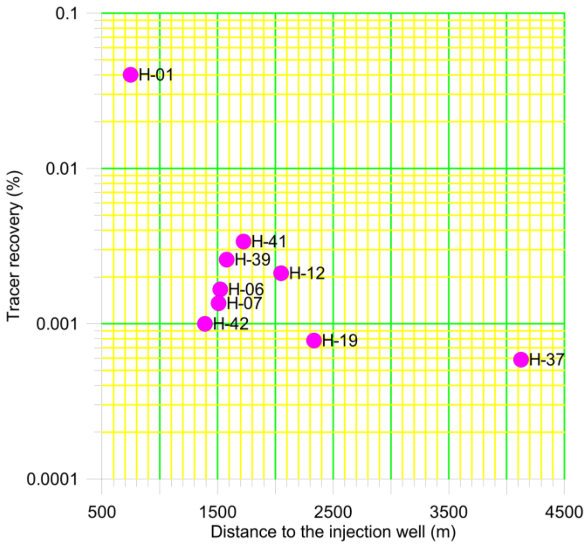

Figure 6: Tracer recovery vs. distance to the injection well

The small recovery percentages found in this study also suggest that thermal interference due to injection in well H-13 is unlikely for the monitored wells at the injection flowrates of this study.

Our results reveal the existence of horizontal permeability over a wide area of the field (e.g., wells H-12 and H-37 are 6 km apart). There is no perceptible correlation between this permeability distribution with the known distribution of faults in Los Humeros (Fig. 2). We suggest this permeability distribution may be associated with contacts between different geologic formations in the caldera.

3.3 Residence curve patterns and their cause

The residence curves of Figs. 2-4 present patterns that differ considerably from the usual ones in tracer studies. They present series of peaks that appear to be of stochastic nature. As mentioned, we had noticed similar patterns in our previous results for this field (Iglesias et al., 2007). In an effort to elucidate the causes of these patterns, we started by observing that during sampling the wells discharges presented short-term variations, both in this and in the previous studies. It is well-known that high-enthalpy wells with two or more feeding zones of different enthalpies tend to present this behavior (Grant et al., 1982). Thus, in order to investigate the causes of the unusual patterns presented by the residence curves in this field we measured the electrical conductivity of all the samples in the present study. Table 3 presents the main statistics of these measurements; the sample size is $n = 80$ for each well. The measured conductivities presented important dispersions, much higher than those attributable to measuring errors.

Table 3: Statistics of electrical conductivity

Well	Electrical Conductivity (μS/cm)			
	Max.	Min.	Mean	Std. Dev.
H-01	1,062.0	370.0	828.6	156.92
H-06	597.0	60.5	236.8	159.00
H-07	840.0	30.6	253.8	209.21
H-12	193.0	101.3	137.7	18.86
H-19	639.0	112.8	365.7	186.87
H-37	1,772.0	893.0	1,366.8	222.06
H-39	847.0	686.0	787.0	29.63
H-41	1,082.0	85.0	196.7	129.74
H-42	712.0	65.7	308.7	202.54

Since the sample electrical conductivity is proportional to its ion density, one would expect higher electrical conductivities in discharges with higher fractions of water. Comparing mean values of electrical measured electrical with the average fraction of water in each well discharge we found a linear correlation (Fig. 7) with a correlation coefficient equal to 0.8460; the black lines represent a 95% confidence interval. Since electrical conductivity reflects ion concentrations in the samples, we infer that discharges with greater enthalpies present smaller electrical conductivities probably because of dilution by condensed steam. The histograms in Figs. 3-5 and the corresponding values in Table 3 indicate that all the observed wells have at least two feed zones with different enthalpies. Thus we infer that the probable cause of the observed variation of the electrical conductivity in the discharges is the existence of multiple feed zones with different enthalpies in the wells.

The correlation in Fig. 7 reveals that the variability of the electrical conductivity in the samples indicates variations in the fraction of water in the corresponding discharge. Therefore, the tracer concentration in the discharge is modulated by the instantaneous fraction of water in the discharge. This modulation is superposed on that produced by the tracer arrival to the interface between the fracture(s) feeding liquid to the well and its wall. And, if there is more than one fracture feeding liquid or steam to the well, the resulting mixtures also modulate the tracer concentration in the liquid discharge. We conclude that this complex superposition of modulations explains the unusual patterns observed in the residence curves of the liquid-phase tracer in Los Humeros. It will be necessary to take this into account in the design of future tracer studies in this field.

4. SUMMARY AND CONCLUSIONS

We injected a liquid-phase tracer in well H-13D of Los Humeros geothermal field and monitored during 272 days its concentration in the water discharges of nine wells designated by CFE.

The tracer was detected in all the monitored production wells, revealing injection in well H-13D recharges the nine observed production wells.

The short arrival times of the tracer to the production wells suggests the existence of an areally extensive distribution of subhorizontal, high-permeability area within the studied zone. This permeability distribution is not obviously associated with the known distribution of faults in Los Humeros; it might be associated with contacts among geological formations.

With the possible exception of well H-01D, the tracer did not complete its arrival to the observed wells. This and the unusual patterns presented by the residence curves caused uncertainty about the magnitude of the expected tracer recovery in each well and on the total expected recovery. However, if the magnitude of the expected tracer recovery were similar or not much greater than that observed in a previous study of a contiguous zone in this field, the recorded small total recovery would indicate that most of the injected fluid is dispersed in the reservoir. A reasonable scenario for this to happen is that most of the injected brine, being colder and denser than the reservoir fluid, flows downwards to depths greater than those corresponding to the feeding zones of the wells, recharging the deep reservoir and enhancing its economic life.

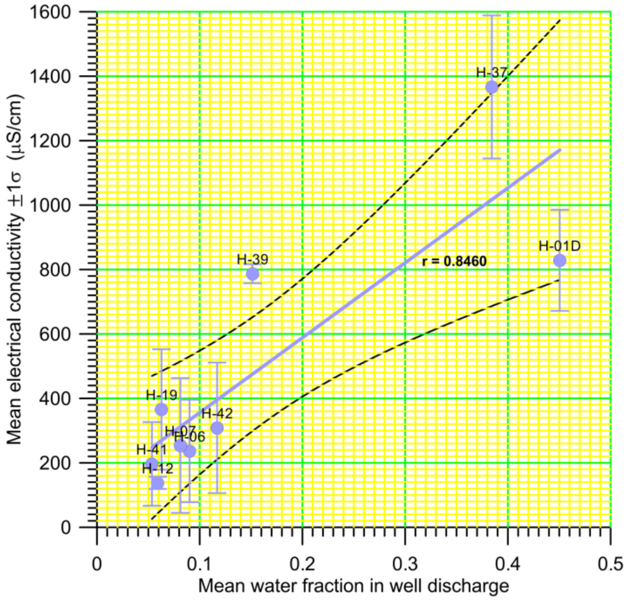

Figure 7: Mean electrical conductivity vs. mean water fraction in the discharge

The small recovery percentages found in this study also suggest that thermal interference due to injection in well H-13 is unlikely for the monitored wells at the injection flowrates of this study.

We investigated the causes generating the unusual patterns of the residence curves in this field. To that end we measured the electrical conductivity of each sample in every well. Comparing the mean values of electrical conductivity measured in each well and that of the fraction of water in the discharge we found a highly significant linear correlation between these variables. Considering the short–term variations observed in the wells discharges, the variations of the fraction of water in the discharges revealed by the variations of the measured electrical conductivity in the samples, and the statistical distributions of the electrical conductivity in each well, we concluded that the cause of the unusual patterns of the residence curves is the existence of at least two feed zones with different enthalpies in the wells.

It will be necessary to take this into account in the design of future tracer studies in this field.

REFERENCES

Iglesias, E.R., Torres, R.J. and Reyes-Picasso, N., 2007, Estudio con trazadores en la zona Norte del campo geotérmico de Los Humeros, Puebla – Primera etapa, Instituto de Investigaciones Eléctricas, Report IIE/11/13360/I-02/F, 105 pp.

Iglesias, E.R., Flores-Armenta, M., Torres, R.J., Ramírez-Montes, M., Reyes-Picasso, N., Reyes-Delgado., L., 2010, Simultaneous liquid- and vapour-phase tracer study in the Tejamaniles área of the Los Azufres, Mexico, geothermal field. Proceedings World Geothermal Congress 2010, 7 pp., paper No. 2227.

Rose, P.E., W.R. Benoit, and P.M. Kilbourne, 2001. The applicaction of polyaromatic sulfonates as tracers in geothermal reservoirs. *Geothermics*, 30, pp. 617-640.

Rose, P.E., Rose, V. Capuno, A. Peh, P.M. Kilbourne, and C. Kasteler, 2002. The use of naphthalene sulfonates as tracers in high temperature geothermal systems. *Proceedings of the 23rd Annual PNOC-EDC Geothermal Conference,* pp. 53-58.

Shook, G.M. and J.H. Foramann, 2005. Tracer interpretation using temporal moments on a spreadsheet. Report INL/EXT-05-00400 Revision 1, Idaho National Laboratory, Idaho, USA.