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THE FIRST MULTIWELL, MULTITRACER TEST IN THE LOS AZUFRES GEOTHERMAL FIELD. PROGRESS REPORT

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ABSTRACT

At the time of submitting this paper we are running the first tracer test in the Los Azufres geothermal field. The main goals of test axe: to probe the concept of using separated spent brines as extremely inexpensive sources of tracers; to detect possible high conductivity hydraulic flowpaths between propective reinjection wells and the nearby production zone in the Tejamaniles area; to monitor reservoir temperatures during tie test in order to obtain valuable extra observational constraints to aid the interpretation; and to field test a number of techniques concerning data gathering and analysis. So far, we have found no evidence of the existence of hydraulic communication between the reinjection and the production zone. Nevertheless, we were able to conclude that the Cl^- and Na^+ dissolved in concentrated spent geothermal brines can be used as reliable and extremely inexpensive tracers for hidrothermal flows, provided that the injectim of the brine is steplike (continuous injection at constant flowrate and concentration). We also found in necessary to monitor reservoir temperatures during the test, by means of both, the Na/K and the silica geothermometers, in order to allow diagnosis of boiling in the reservoir, which can cause $[Cl^-]$ and $[Na^+]$ to increase independently of the arrival of a chemical front.

INTRODUCTION

The use of tracers in geothermal environments has been the subject of a continuosly growing interest during the last few years. For example, the number of papers dealing on the use of artificial tracers in the Proceedings of the Stanford Geothermal Reservoir Engineering Workshop increased monotonically fran none in 1980 to 7 in the current issue. This interest stems from the ever wider recognition of the economic and technical advantages offered by the reinjection of spent brines, and fran the perceived risk of possible concomitant thermal interference between reinjection and production wells.

In Mexico, this interest prompted work that, to date, resulted in two published papers (Flores et al., 1982; Iglesias and Hiriart, 1981). The paper by Flores et al described the first tracer test run in t ! Cerro Prieto geothermal field. The paper by Iglesias and Hiriart dealt with the earliest efforts to conduct tracer tests in the geothermal field of Los Azufres. It reported on the design of a multitracer test for the Tejamaniles area of the field, planned for early 1932. In this test, conventional (bromide and iodide) and unconventional (thiocyanate) geothermal tracers were to be used. Unfortunately, the onset of the country's current economic crisis prevented us from carrying out that test as *scheduled*.

Ways were then sought to reduce the costs of geothermal tracer testing in general (Iglesias 1982), and to design an economically feasible tracer test for the Tejamaniles area, in particular. These efforts eventually resulted in the concretion of the first tracer test in Los Azufres, which at the time of writing this paper is still in progress.

The present work reports on the current test. The main goals of the test are: to probe the concept of using separated spent brines as extremely inexpensive sources of tracers; to detect possible conductivity hydraulic flowpaths between prospective reinjection wells and the nearby production zone in the Tejamaniles area; to monitor reservoir temperatures during the test in order to obtain valuable extra observational amstraints to aid the interpretation; and to field test a number of techniques concerning data gathering and analysis.

A conventional "slug" test, using non-radioactive iodide as the tracer, is being run simultaneously with the test reported in this paper. The iodide test is a joint effort by Instituto de Investigaciones Eléctricas, Stanford University, and Comisión Federal de Electricidad. Its results will be reported elsewhere.

SPENT BRINES AS SOURCES OF TRACERS

Field tested artificial geothermal tracers that proved conservative are relatively few. By a conservative tracer we mean one that, while in the reservoir, does not undergo chemical or physical changes (e.g. chemical reactions with fluid or rock, adsorption) which could partially or totally prevent its recovery. These identified conservative tracers include radioactive and non-radioactive bromide and iodide (e.g. Mc Cabe et al., 1981; Tester et al., 1982; Horne, 1982), tritiated water (e.g. Einarsson et al, 1975), and, possibly, radioactive iridium (Flores et al., 1982). These substances are relatively expensive: the tracer cost of a typical test runs on the thousands to tens of thousands of dollars for one injection of one tracer. As mtioned, we made some efforts to come up with inexpensive tracers adequate for geothermal use.

Of the ideas considered, one of the mst promising turned out to be the use of separated *geothermal* brines as very inexpensive sources of adequate tracers.

In high enthalpy geothermal fields, spent brines separated at atmospheric or production separator pressures, are substantially more concentrated than reservoir brines, due to significant *steam* losses. For example, in U s Azufres, brines separated at atmospheric pressure are typically about twice as concentrated as the original brine at depth. The concentration contrast is therefore modest by the usual *standards* in "impulsive" or "slug" tests. In this type of test, a relatively small amount of fluid, marked with a very high cancentration of the chosen tracer, is injected *over* a period of time that is very short with respect to the duration of the *test'*. This produces a peaked distribution of tracer concentration, which increases in width and &creases in height as it propagates in the resew~*. The change of shape of the peak is due mainly to dispersion and conservation of mass. Thus, in order to be able to detect the tracer, the initial concentration contrast and consequently the initial heigh of the peak, must be in *general* much greater than the background concentration of the tracer in the reservoir or the resolution of the detection technique, whichever is greater. Consequently the modest concentration contrast of the separated brines make them generally inadequate for use in the usual *"impulsive"* or "slug" tests.

However, separated brines can be used as sources of tracers if a step-like instead of a peak-like injection pattern is adopted. In the former type of test, starting at a certain time, fluid marked with the tracer(s) is continuously injected at constant flowrate and constant tracer concentration throughout the duration of the test. *As* a result, the tracer propagates in a pistan-like fashion, the tracer frant resembling a step function near the injection well. The tracer front increases in width as it propagates, due to dispersion, as in slug tests. However, in this *case* the injected mass of tracer is not a constant, but increases linearly with time, and the height of the front remains constant as it propagates. Consequently, the initial concentration contrast required for this type of test is much smaller than for slug tests. In fact, concentration contrasts as small as a few times the resolution of the detection technique can be used and still obtain qualitative results.

Obviously, the great amount of tracer required *by* "step" tests would make than economicallv prohibitive if the conservative artificial tracers mtioned at the begining of this *section* were to be used. Fortunately, spent brines are usually available aplenty, and at a nil *cost,* when observation wells are produced during tracer tests. The preceding discussion indicates then that step tests using spent brines as sources of tracers are both technically feasible and economically convenient.

The brine of U s Azufres is typically *geothermal*, and consists mainly of a sodium chloride solution. Table 1 *shows* approximate ranges of concentrations for various components of interest in brines separated at atmospheric pressures. The ranges quoted *cover* the compositions corresponding to *several* wells; the spread reflect mstly reservoir temperature effects.

Table 1. Representative compositions of U s Azufres brines separated at atmospheric pressure. (Nieva, 1983).

Component	Concentration Range (ppm)
Na^+	1563 - 1778
K^+	289 - 446
Li^+	16 - 29
Ca^{2+}	7 - 24
Mg^{2+}	0.008 - 0.4
Cl^-	2650 - 3076
Br^-	1 - 5
I^-	0.43 - 0.49
SiO_2	750 - 870

Experience indicates that cations do not propagate through reservoir formations as easily as anions (e.g. Wagner, 1977). In particular, the halogen anions are known to be conservative. Of the available halogen ions we chose chloride as our main tracer candidate. The principal reasons for this choice were its abundance, and that it is much easier to analyze *by* wet chemistry techniques than either bromide or iodide, which *are* also *present* in the brine.

As secondary tracer candidates we chose Na^+, K^+, and Li^+. We thought that, despite their suspect status as conservative tracers, and the temperature dependance of their concentrations they should provide at least qualitative *checks* on the performance of chloride. Moreover, these cations were relatively *easy* to analyze by techniques available to us. Finally, Na^+, K^+, and Li^+, provide ways to monitor reservoir temperatures during the test.

MONITORING RESERVOIR TEMPERATURES

When a cold spent brine is reinjected step-wise into a geothermal **reservoir,** a chemical **as well as** a **thermal** front propagate **as** a result. The chemical front arises from the concentration contrast **between** the reservoir brine and the reinjected brine. The thermal front arises from the corresponding temperature contrast. In general one expects the **thermal** front to **lag** behind the chemical front, due to heat transfer **from** the **hot rock** to the cool reinjected brine. If the breakthrough of both fronts could be recorded in **an** observation well, the time lag **between** the fronts would provide very valuable information for the interpretation of the **test.** For practical **test** durations, only very **high** hydraulic transmissivity **channels** offer hope of recording both fronts for typical geothermal interwell distances. **Lower** transmissivities and unchanneled, **porous medium-type** flaws imply much larger heat transfer **areas,** and significantly increased residence times for the thermal front.

The **reservoir** formations in Los Azufres **are** mainly tight volcanic rocks. For that reason the fluid flow is believed to take place mainly through fractures. **Thus** the reinjection and **production** zones might be linked ***by* high** hydraulic transmissivity fractures , suggesting that a dual **chemical/thermal breakthrough** could **be observable in the test area. This was one** of the **main reasons** why we decided to monitor the temperature during the test.

Other reasons **were** the possibility of picking up some *other* **temperature** effects occurring in the reservoir, which would provide additional constraints for the interpretation of the test: and that of assesing the technical and logistical **advantages** and difficulties associated with the **concept.**

Of the available alternatives **we** chose a Na-K **geothermometer (Nieva** and Nieva, **1982) and** a ***silica*** geothermometer (Fournier and **Potter, 1982). The** later **reflects** the **reservoir** temperature in the **neighborhood** of the producing well, **due** to the fast reequilibration of ***silica*** upon **temperature** *changes.* The former provides the **temperature farther away** in **the reservoir, *on* account** of the **much** slower **reequilibration** of sodium and potassium **ions.**

In order to use the silica **geothermometer,** diluted, acidified fluid samples must **be** collected. **On** the **contrary,** the **use** of the Na-K **geothermometer** does not require special samples: the brine samples taken to monitor the selected **tracers are adequate** to **this *end.* This** is a desirable feature that simplifies the logistics of the **test.**

To conclude **this** section, **we** shall refer to the **techniques** of analysis **assessed** during the test. **Two techniques** were tried for the analysis of Na, K, **and** Li: flame **photometry** and spectrophotometric atomic **absorption.** Silica **was** analyzed by the **standard** molybdate blue colorimetric method.

TEST AREA

The test area is located in the **Tejamaniles** region, ***on*** the southern **portion** of the field (Fig. 1). The planned reinjection wells **A-7** and **A-8** lie **on** the *southwestern* edge of the field, **as indicated *by*** geologic and resistivity data. **Several** hundred *wters* east of the designated **zone** lie **A-2** and **A-16,** the observation **wells** in **this** test. **These** four wells produce **steam** and **water.** The depths, slotted intervals, and **inter well distances** of interest **are given in** Table 2. These slotted **intervals intercept** mstly microlitic andesites with **some** interspersed dacite and porphyritic **andesite in well A-7.** In **these** tight igneous rocks the fluid flow is thought **to** occur mainly through **fractures. Note** that the **slotted intervals** of wells **A-7 and A-8** (i.e., the reinjection **intervals)** lie **deeper that the slotted** intervals of the observation **wells, except** for the upper **interval** of **well A-7,** which partly **overlaps the** p[illegible] **intervals.** This depth offset **is** a desirable feature for a **reinjection** setup because the negative bouyancy of the colder and denser reinjected **water** tends to delay **thermal** interference. **By the same token, this** feature may affect tracer **recovery.**

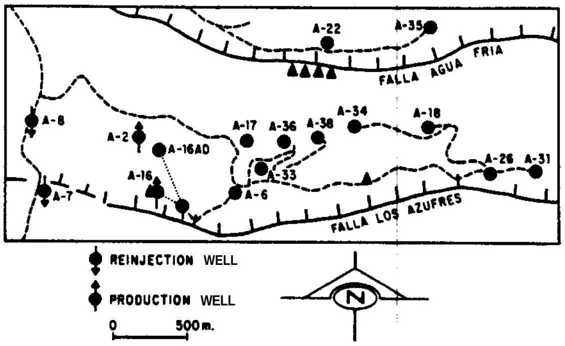

Fig. 1. Location of the wells.

Fast of the observation wells **there** is a group of **wells (A-6, A-17, A-36, A-38, A-34)** that produce **dry** steam **and two** wells **(A-16AD and A-33)** that produce mstly wet steam **and** a little **water. Note** that **wells A-16 and A-16AD are** directionally **drilled** from the **same** wellhead **location.** Data **pertaining to A-16AD has been added** to Table **2 due to the proximity** of this well ***to*** the reinjection area. **For** technical **reasons** well **A-16AD was not monitored** during the test. Other wells **shown** in Rig. **1 are too** far from the reinjection zone ***to*** be of interest for the test.

Table 2. Well data

well	A-8	A-7	A-2	A-16+	A-16AD+
Wellhead height above sea level (m)	2775	2750	2750	2825	2825
Depth (m)	2301	1706	1130	1285	855
Open intervals (m)	1991-2299	1049-1098 1296-1580 1665-1690	1039-1130	1072-1285	760-850
Distance to A-7 (m)	500	--	740	760	840
Distance to A-8 (m)	--	500	750	980	890

+ well directionally drilled.

THE TEST

The test started August 2, 1983. Reinjection of brine produced by well A-16, separated at atmospheric pressure (~0.7 bar), began in well A-7. The reinjection temperature was about 60°C at the wellhead of A-7. The average reinjection rate was 35 ton/hr. This flowrate has been maintained reasonably constant since the beginning of the test.

Hot brine, produced by well A-2, was also reinjected in well A-8. Unlike the former case, this brine was separated at several bars, by means of a production separator. Thus the concentration contrast of this brine was smaller than that of the brine reinjected in A-7. Unfortunatelly, neither the separation pressure, nor the reinjection flowrate could be kept reasonably constant in the A-2/A-8 doublet due to a host of technical difficulties. The difficulties arose mainly from peculiarities of the producing well A-2, which would not sustain a constant flowrate; from faulty surface equipment (e.g. two wellhead valves developed leaks and had to be changed in different occasions); and from the characteristics of the terrain in which well A-2 is drilled. The terrain proved weak: surface manifestations, not apparent at the beginning of the test, developed upon sustained production. The surface manifestations included steam flowing upwards around the casing, widespread discharges of gases and steam around the wellhead, and even a small mud volcano which eventually grew to be ~3 m long by ~ 0.5m wide. Steam percolating through the ground eventually damaged the wellhead cellar and the foundations of several pieces of surface equipment. This in turn resulted in dangerous mechanical vibrations. These developments forced the decision of taking well A-2 out of production on 31 October 1983. Reinjection in A-8 was simultaneously terminated. Production of A-16 and reinjection in A-7 were not affected, however.

Sampling at the wellheads of A-2 and A-15 started before reinjection (e.g. Fig. 2) to obtain the necessary concentration baselines. The samples were collected in 500 cm3 plastic bottles previously washed with a solution of nitric acid. In order to obtain good time resolution for the breakthrough curves, the sampling frequency during the test was chosen to be proportional to the inverse of the square root of the time elapsed since the beginning of the test ($f = f_o/\sqrt{t}$). This non-uniform sampling strategy was adopted because the width of the tracer front is expected to increase proportionally to $\sqrt{t}$ in most situations (Bear, 1972), and because breakthrough times, unknown a-priori, could vary over several orders of magnitude according to the type and magnitude of the hydraulic transmissivity existing between the injection and production wells. For the interwell distances involved in this test, breakthrough times as short as several hours were possible a-priori, since tracer velocities as high as 80 m/h have been recorded in similar volcanic settings (Horne, 1982).

RESULTS AND DISCUSSION

The difficulties encountered in controlling the wellhead pressure and flowrate of the observation well A-2 complicated the interpretation of the corresponding data. The complications arise mainly from the non-uniform sampling conditions induced by frequent changes of wellhead and/or production separator pressures, and from the effects of these changes on the chemical composition of the produced fluids which are difficult to predict reliably, Chemical composition changes associated with variations of flowrate have been recorded both in A-2 and in 3-16, and will be illustrated below. Due to these complications, and to the necessity to meet the deadline for this progress report, we shall postpone reporting on our results from A-2, and will concentrate instead on the more straightforward results corresponding to the other observation well, A-16.

Figure 2 presents the early data on the concentrations of Cl$^-$, Na$^+$, K$^+$ and Li$^+$ for well A-16. (Hereafter concentrations will be denoted by square parentheses). These data nicely illustrate chemical composition changes induced by sudden variations of flowrate. On August 1st, at 10:00 hrs the well was open. The Cl$^-$ concentrations, from samples taken every 15 minutes, recorded a rapid increase of more than 12% in about 2 hours. These samples were not analyzed for Na$^+$, X$^+$ or Li$^+$. The well was then shutin at 13:00 hrs. Then, at 17:25 hrs the well was opened for the second time. Again a rapid increase of [Cl$^-$] was recorded. This behavior was closely imitated by [Na$^+$], [K$^+$] and [Li$^+$], as shown. Later, on August 2nd at 11:30 hrs, the flowrate was increased. This was immediately reflected by sharp increases of the concentrations of all the ions monitored (Fig. 2). These sharp increases were short-lived however, and the ion concentrations shot back to nearly their stabilized values previous to the increase of flowrate, in about 15 minutes. Finally, at 12:20 hrs the flowrate was turned back to its initial value, with no apparent change of the ion concentrations. These results indicate that increases of flowrate are accompanied by transient increases of the concentrations of the ions in solution, and that the ulterior evolution of the increased concentrations depends on the history of the flowrate.

The results presented in Fig. 2 also show that [Cl$^-$] has the smallest dispersion. It is therefore the most sensitive of the candidate tracers. The smaller dispersion of [Cl$^-$] is due to several causes, including the characteristics of the techniques of analysis used to obtain the results of Fig. 2, and the fact that Cl$^-$, being a major component, is virtually free of interferences. Chloride was analyzed by a standard "wet" chemistry method, (Mohr's); the results for [Na$^+$], [K$^+$], and [Li$^+$] shown in Fig. 2 were obtained by flame photometry. Smaller dispersions for [Na$^+$] and [K$^+$] were eventually obtained using spectrophotometric atomic absorption, as shown below. Despite the improvement, however, Cl$^-$ remained the most sensitive of the candidate tracers.

The increase of the ion concentrations that followed the opening of the well (Fig. 2) cannot be ascribed of course to the arrival of the chemical front because reinjection did not start until August 2nd at 17:00 hrs, nearly 24 hours after production began.

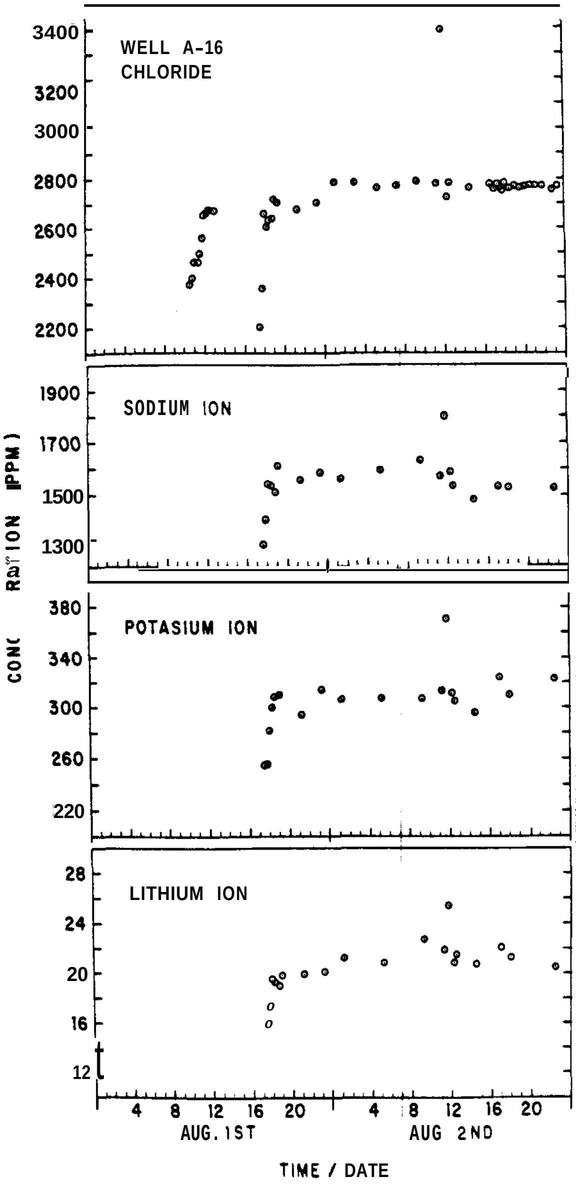

Fig. 2. Early ion concentrations in well A-16

The time scale of the concentration changes just discussed ranged from minutes to hours. Next we shall address concentration variations with much larger time scales. Figure 3 depicts the long-term evolution of [Cl$^-$] for well A-16. For nearly two and a half months [Cl$^-$] increased at an average rate of about 1.63 ppm per day. Then, on the evening of October 13 the flowrate was significantly increased, by mistake. The high flowrate was maintained for about 18 hours. This event seemingly damaged the well: neither the flowrate, nor the wellhead pressure recovered to their pre-event values when flaw through the original orifice was resumed. Right after the event, $[Cl^-]$ oscillated wildly for a few days. Afterwards $[Cl^-]$ developed a haphazard pattern (Fig. 3).

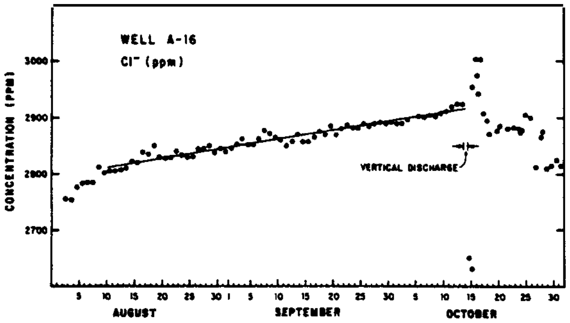

Fig. 3. Long-term evolution of $[Cl^-]$ in well A-16

The general behavior of $[Cl^-]$ was closely followed by $[Na^+]$ for sane time (Fig. 4). The slope of the *straight* line depicted in Fig. 4 is 1.64 ppm/day, almost exactly the value of the slope found for $[Cl^-]$. However, starting approximately September 25, $[Na^+]$ flattened out, unlike $[Cl^-]$ that kept increasing linearly until the event described above. This departure of $[Na^+]$ from the trend depicted by $[Cl^-]$ very likely indicates a systematic error of analysis for Na^+, for the October samples, which were analyzed in one batch. This is *suggested* also *by* conservation of charge, given the reliability of our Cl^- analysis.

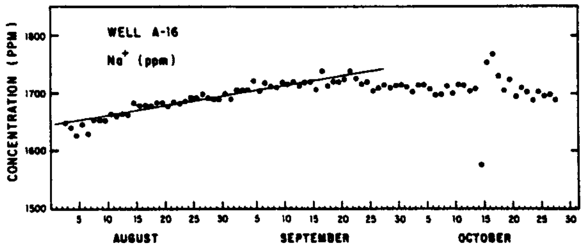

Fig. 4. Long-term evolution of $[Na^+]$ in well A-16

The pre-event evolution of $[K^+]$ differed significantly from the trend observed for $[Cl^-]$ and $[Na^+]$ (Fig. 5). The slope of the *straight* line of Fig. 5 (0.41 ppm/day) is only a fraction of the common slope of $[Cl^-]$ and $[Na^+]$. only during the brief early period that *ends* about *August* 14 the slope of $[K^+]$ is similar to *that* of the major ions.

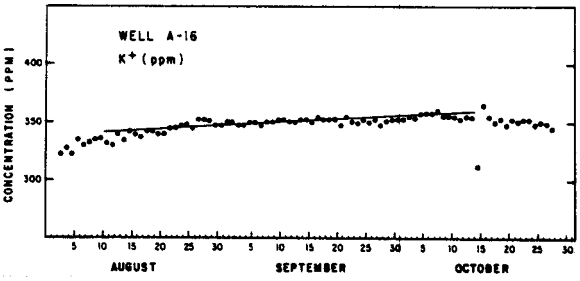

Fig. 5. Long-term evolution of $[K^+]$ in well A-16

We interpret the behavior of $[Cl^-]$, $[Na^+]$, and $[K^+]$ just discussed as caused by boiling of the fluid in the reservoir, near the well. Boiling would be induced *by* pressure drawdown due to production. This interpretation is suggested by the results of the geothermometers (Figs. 6 and 7): the temperature of the boiling fluid near the well, calculated with the silica geothermometer, is lower than the temperature of the fluid farther away in the reservoir represented *by* the Na/K geothermometer, as expected when boiling occurs around the wellbore in the reservoir. Furthermore, the increases of $[Cl^-]$ and $[Na^+]$ indicate either pressure drawdown, or increasing specific enthalpy, or both, as required *by* boiling in the *mix* near the well.

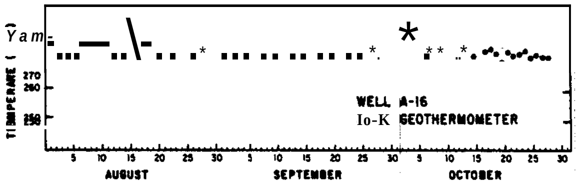

Fig. 6. Temperature of the fluid far away in the reservoir, as measured by the Na/K geothermometer.

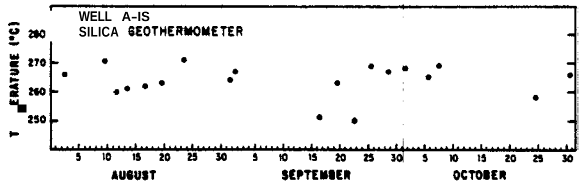

Fig. 7. Temperature of the fluid in the reser*voir*, near the producing well, as measured *by* the silica geothermometer.

The results of the geothermometers (Figs. 6 and 7) help interpret the observations just discus*sed.* The scatter of the temperatures derived with the silica geothermometer is significantly greater than that of the temperatures obtained from the Na/K geothermometer. Currently we believe that the scatter of our silica results may be due mainly to errors of dilution in the samples. One way to decrease these errors would be to rely on weight rather than on volume measurements to better control the dilution of the samples.

The results discussed above show that changes as small as a few percent in the concentrations of the major ions Cl^- and Na^+ of produced geothermal brines can be reliably detected by standard techniques of analysis. Tracer returns of about 10% of the injected amounts are typical of fractured reservoirs (e.g. Mc Cabe et al, 1981), and greater recovery ratios are usually observed in porous reservoirs. Therefore, we conclude that it is technically feasible to use Cl^- and Na^+ from concentrated reinjected brines as tracers for geothermal fluids. However, the causes that can provoke increases in [Cl^-] and [Na^+] include, besides the arrival of a chemical front, boiling in the reservoir, as discussed. In this particular case we were able to distinguish between these causes by supplemeting the information given by [Cl^-] and [Na^+] with that provided by the silica and Na/K geothermometers, and because we knew that the initial increases of the chemical concentrations could not possibly arise from the arrival of the chemical front.

The case where no boiling occurs should be recognizable by the lack of significant differences among the results of the silica and Na/K geothermometers.

The interpretation of the more complex case in which both the effects of boiling and of the chemical front overlap, should be helped by the likely existance of significantly different time scales associated with these effects. To conclude this section we note that the data available so far do not support the existence of hydraulic communication between the production and the reinjection areas.

SUMMARY AND CONCLUSIONS

At the time of writing this report we are running the first tracer test in the geothermal field of Los Azufres. In this test we are attempting to use ions dissolved in the concentrated reinjected brines as extremely inexpensive tracers, and to monitor the temperature in the reservoir during the test by means of the silica and the Na/K geothermometers. So far the test has been running for about 90 days. The following conclusions can be drawn from the existing data:

The Cl^- and Na^+ dissolved in concentrated spent geothermal brines can be used as reliable and extremely inexpensive tracers for hydrothermal flows, provided that the injection of the brine is steplike (continuous injection at constant flowrate and concentration). The K^+ and Li^+ ions are not as reliable as geothermal tracers due mainly to the sensitive temperature dependence of their concentrations.

Chloride, being a conservative major anion, essentially free of analytical interferences, and easily and reliably analyzed, is the preferred tracer.

It is strongly advisable to monitor [Na^+], [K^+], and [SiO_2] during the test, in order to allow diagnosis of boiling in the reservoir, which can cause [Cl^-] to increase independently of the arrival of a chemical front. Comparison of the temperatures derived from the Na/K and from the silica geothermometers indicates whether boiling is occurring in the reservoir near the producing well (s). Furthermore, knowing [Cl^-], [Na^+], and [K^+] for particular samples allows checks of the reliability of the analytical results, by conservation of charge.

So far, we have found no evidence of the existence of hydraulic communication between the reinjection and the production zone.

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