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DESIGN OF A TRACER TEST FOR THE GEOTHERMAL FIELD OF LOS AZUFRES, MICHOACAN, MEXICO: PROGRESS REPORT

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ABSTRACT

A tracer test will be conducted at the Los Azufres geothermal field to detect possible high permeability flowpaths interconnecting reinjection and production wells, in order to asses reinjection feasibility in the Tejamaniles area. This test will be the first of its kind to be conducted in this geothermal field. Tracers will be injected in wells **A-7** and **A-8**; **A-2 will** constitute the main observation well. This study suggests that other wells, including probably **A-16**, **A-1**, **A-22** and **A-18**, should also be mnitored. Continuous production/reinjection will provide the driving force for interwell flow. To speed up results, simplify logistics, and reduce costs, slugs of two different tracers, each identifying a particular well, will be simultaneously injected. We *chose* anions as tracers because they propagate through reservoir formations with negligible absorption, and considering the availability of equipment for their analysis. Several bromide, iodide and thiocyanate salts were considered as prospective tracer sources. The unknown background iodide concentrations in the reservoir were determined by us. We estimated the amounts of the prospective salts to be injected by means of Lenda and Zuber's method, and computed the corresponding costs. Considering these amount-cost calculations and that bromide and iodide have been extensively tested in geothermal environments, we chose these anions as the main tracers for the test. As a complement, we propose to conduct a field experiment to evaluate thiocynate as a geothermal tracer.

INTRODUCTION

The Los Azufres geothermal field is located 19°49'N, 100°39'W on the Transmexican Neo-Volcanic Axis. The field consists of highly fractured neo-quaternary volcanic deposits. Production horizons are mstly andesites, but in some cases include dacite. Because of the tightness of these igneous rocks the main production is believed to proceed through fractures.

The reservoir is liquid-daminat&, but there is a steam cap located near wells **A-6** and **A-17**, in the Tejamaniles region. Produced waters are of medium salinity: TDS ∿ 5000-8000 ppm for separated brines (Templos y García, 1981) These brines contain silica **(900-1300 ppm)**, boron **(150-250 ppm)**, arsenic **(15-30** ppm), and traces of mercury (Templos y García, 1981). Such amounts of ecologically nocive substances are not suitable for untreated surface disposal. Thus, reinjection of the spent brines is considered as one alternative for disposal.

&injection of relatively cold spent brines, apart from solving the disposal problem, *may* be beneficial to maintain reservoir pressure (e.g. Cuellar et al, **1978**; Home, **1981)**. But thermal interference may also result from reinjection (e.g. Einarsson et al, **1978**; Home, **1981)**, with potentially serious economic consequences due to enthalpy drawdown. Tu avoid the detrimental effects of thermal interference, two reinjection strategies may be adopted: (a) to reinject into formations hydraulically isolated from the producing reservoir; or (b) to reinject at a distance from the producing wells such that the reinjected water has time to reheat before being produced. This "safe distance" depends sensitively on the details of the local pemability. For example, in Ahuachapan a tracer arrived at a well 400 m distant from the reinjection well in two days, but the corresponding arrival times far two other wells located **450** m and **1000** m from the injector were several weeks (Einarsson et al, **1978)**. Thus, identification of high permeability paths interconnecting planned reinjection-and production-wells should preceed the actual implementation of a reinjection *schene.* Tracer tests constitute an unsurpassed reservoir engineering tool to detect such short circuiting flowpaths.

This paper reports on the design of a tracer test that will be run in the Los Azufres geothermal field. The test will involve wells **A-7** and **A-8** as reinjectors, and well **A-2** as the producer. The main goals are (a) to detect possible high permeability flowpaths linking the planned reinjector wells with **A-2**; and (b) to interpret the data, either in terms of fracture conductivity or of matrix permeability.

In the following sections we describe the test area, and discuss the design of this first tracer test in Los Azufres.

TEST AREA

The test area lies in the Tejamaniles region (or module, as they have been termed), in the southern portion of the field (Fig. 1).

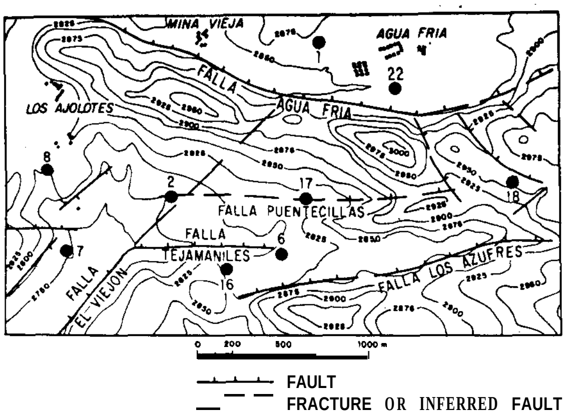

Fig. 1. Map of the Tejamaniles and Agua Fria modules.

Planned reinjection wells A–7 and A-8 lie on the western *edge* of the field, as inidicated by geologic and resistivity **data** (Garfias, 1981). Their depths, open intervals, and distances to other wells **located** in the Tejamaniles and **Aqua Fria** modules are given in Table 1. East from A-7/A-8 the distribution of temperature is dome-like, with its maximum *near* wells A–6 and A–17. This is reflected in the depths of the wells drilled in the Tejmiles module.

Production well A–2 is **located** several hundred meters East from the planned reinjectors. The completions and lithological columns of wells **A-2**, **A-7** and **A-0** are shown in Figure 2. The production and reinjection intervals intersect mostly microlitic andesites, with *some* interspersed dacite and porphyritic andesite in well A–7. In these tight ingneous rocks the flow is thought to come mainly through fractures. Note that the reinjection intervals lie deeper than the production interval of A–2, except for the upper slotted interval of well A–I which overlaps it. This is a desirable feature for a reinjection scheme because the negative bouyancy of the colder and denser reinjected water **tends** to delay thermal interference: but may add some difficulty to the recovery of tracers. However, there is indication of hydraulic connection of wells A-7 and A-8 With A–2, from an Bylier interference test (Hiriart, 1980).

Other neighboring wells, in addition to **A-2**, were included in Table 1 for completeness. Of these, A–16 is the second closest to the reinjection area. Well A–16 was first drilled vertically to a depth of 2500 m. High temperatures but low permeabilities were found. Recently the well was reentered and directional drilling began from a **depth** of ∿ 500 m. At the time of this writing the directional well had succesfully intersected the Tejamaniles fault. The depth and distances to well A-7 and A-8 given in Table 1 were estimated *by* us. At the time of this writing the productivity test had not **started. Thus, it** is not known whether *dry* **steam** or a two-phase mixture will be produced. If the **produced** fluid turns out to be two-phase, **it** is *expected* that A–16 will be kept bleeding through a small diameter line throughout the duration of the tracer test. In that *case,* the separated **water** will be monitored for tracers.

Farther East from the reinjection area lie wells **A-6** and A–17. These relatively shallow wells produce *dry* **steam.** The chemical tracers we *are* planning to use in **this** first test partition negligibly into the gas phase. **Therefore** these wells will not be monitored during the tracer test.

Next in increasing distance from the reinjection area is well A–1, **located** to the **NE** of A-7/A-8 in the *Agua* Fria module (Fig. 1). This well is currently producing 30 tons/h with a water/steam ratio of 2:1. It is expected that this flowrate will be kept constant throughout the duration of the tracer test. If that is the case, the separated water will be monitored for tracers.

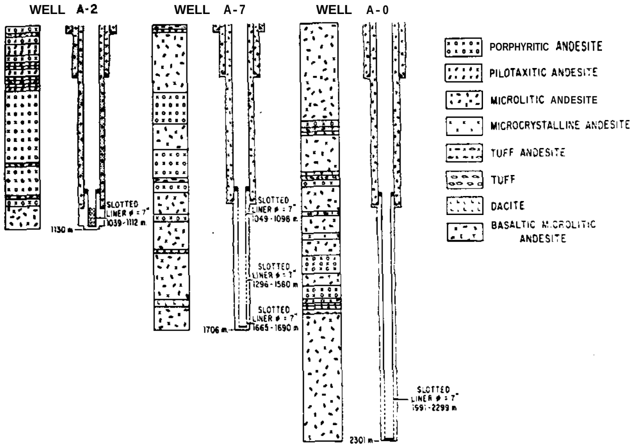

Fig. 2. Lithological columns and completions of wells A–2, A–7 and A-8.

Finally, **wells** A–22 and A–18, in the Agua Fria and Tejamaniles modules respectively, are the farthest from the reinjection area. These wells are *expected* to be kept bleeding through small diameter lines throughout the duration of the tracer test. Due to their negigible productions and great distances from the injection points, there is little **hope** of actually detecting tracers in these wells. Nevertheless they will be monitored on a low priority basis throughout the test.

TEST DESIGN

General Remarks

The test will be conducted in multitracer, continuous production/reinjection mode, as follows. Simultaneous production/reinjection will begin some time before actual tracer injection to allow as much stabilization of the flow in the reservoir as practically possible. Separated water being produced from A-2 will be concomitantly reinjected in wells A-7 and A-8. After a convenient stabilization time has elapsed, short injections of two different tracers, each identifying a particular well, will be inserted in the lines feeding A-7 and A-8. Sampling of well A-2 will begin immediately afterwards. During the first several hours samples will be extracted every half hour; subsequently, the rate of sampling will decrease monotonically. The rationale for this sampling strategy is to record possible early rapid buildup of tracer concentration in A-2 due to high permeability path(s) extending from one or both reinjection wells; as arrival times increase so do dispersions, and tracer concentration buildups become slower, therefore sampling frequency can be safely decreased.

Tracers used in hydrogeology and in the oil and geothermal industries include radioactive substances and chemicals. Use of radioactive tracers involves lengthy proceedings to obtain licenses and equipment currently unavailable to us. For simplicity chemical tracers were adopted.

The main advantage of the approach described in the preceding paragraphs is that the multitracer configuration insures a significantly shorter test. Consequently, logistics can be made simpler, costs (e.g. associated with personnel and equipment) can be reduced, and results will be available earlier.

Tracers

The popular chemical tracers mentioned in the literature can be broadly divided in fluorescent dyes and salts with detectable cations or anions. Fluorescent dyes tend to be retained in the reservoir rocks (Wagner, 1977) and were not considered for this test. Experience has indicated that cations do not propagate through reservoir formations as easily as anions. Thus, only anions were considered as tracers. After screening, the following candidate salts were selected: sodium bromide (NaBr), sodium iodide (NaI), potassium iodide (KI), ammonium thiocyanate (NH_4SCN), and sodium thiocyanate (NaSCN). These salts have suitable anion to molecule molecular weight ratios and high solubilities (Table 2). High solubilities are desirable because they determine the maximum concentration attainable at the point of injection, which generally should be as high as possible in slug injection tests to insure detectability over long distances.

Chemicals with high tracer-anion/salt mass ratios are convenient to keep amounts of salts injected and costs down. Iodide and bromide have been succesfully used as tracers in geothermal environments (e.g. McCabe et al, 1980, 1981; Tester et al, 1979); thiocynate (although fairly common in the oil industry) has not, to our knowledge.

Background Concentrations

The natural (background) reservoir concentrations of the chemicals used as tracers are important for tracer test design because they are related to the amounts of tracers to be injected, as shown later in this paper. In the following paragraphs the background concentrations of iodide, bromide, and thiocyanate in the test area are discussed.

Bromide concentrations are routinely determined by CFE's* geochemistry group in Los Azufres. Average values for separated waters from wells A-2, A-7 and A-8 are 0.29 ± 0.28 ppm, 0.35 ± 0.10 ppm, and 0.2 ± 0.2 ppm respectively (Lopez and Templos, 1980).

Iodide concentrations are not routinely determined in Los Azufres. Sampling and analysis was conducted by an IIE† team in October 1981; CFE personnel collaborated taking downhole samples from well A-7. Iodide concentration resulted as follows: for separated water from A-2, 0.35 ± 0.01 ppm; for two downhole samples from A-7, corresponding to depths of 1075 m and 1420 m, 0.18 ± 0.01 ppm and 0.17 ± 0.01 ppm respectively; for water from the disposal pond of well A-18 (samples taken near the discharge tube), 0.23 ± 0.01 ppm.

Allowing for dilution of the samples from separated water, and considering the known downhole values, we conservatively adopted reservoir "background concentrations" of 0.40 ppm and 0.25 ppm for bromide and iodide respectively. Thiocyanate is generally absent from geothermal waters. Its concentration in the reservoir brine was assumed not to exceed 0.01 ppm.

Amounts and costs

The amount of tracers to be injected were estimated following a method devised by Lenda and Zuber (1970). Normalized breakthrough curves for line injection between two impermeable layers computed by these authors were used. This method assumes that the flow takes place in a homogeneous porous medium with matrix pemability. These assumptions might not apply to the igneous formations characteristic of the test area. Nonetheless, they provide a conservative, "worst case" approach to the tracer flow: generally, in a two well injection

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* Comisión Federal de Electricidad

† Instituto de Investigaciones Electricas

Table 1 Wells directly involved in test, and wells in nearby areas

	Tejamaniles Module							Agua Fria Module	
Well	A-8	A-7	A-2	A-16+	A-5	A-17	A-18	A-1	A-22
Wellhead height above sea level (m)	2775	2750	2750	2825	2800	2810	2950	2875	2875
Depth (m)	2301	1706	1130	1285*	900	627	1328	2173	1560
Open intervals (m)	1991-2299	1049-1095 1296-1580 1665-1690	1039-1130	1072-1285 *	548-581	361-622	1013-1324	1725-2160	1007-1350
Distance to A-7 (m)	500	-	700	740*	1250	1460	2670	1950	2180
Distance to A-8 (m)	-	500	730	960*	1450	1550	2760	1800	2130

+ Well directionally drilled   * Estimate by the authors

Table 2. Chemical properties of prospective tracers*

Tracer	Ratio of molecular weights (anion/ molecule)	Solubility (g/100 c.c.) In cold water	In hot water
NaBr	0.768	116	121
NH_4SCN	0.763	128	very soluble
NaSCN	0.716	139	225
KI	0.764	128	208
NaI	0.846	184	302

*From the Handbook of Chemistry and Physics, 60th Edition, CRC Press.

Table 3. Tracers amounts vs. costs

Tracer	Relative price* per unit mass	Peak anion concentration in breakthrough curve (ppm)	Relative amounts of salts to be injected Well A-7	 Well A-8	Relative cost of salt to be injected Well 7	 Well 8
NaBr	1.00	0.60	1.000	1.148	1.000	1.148
NH_4SCN	1.37	0.10	0.168	0.192	0.230	0.263
NaSCN	1.42	0.10	0.179	0.205	0.254	0.291
KI	14.51	0.35	0.586	0.673	8.503	9.765
NaI	18.23	0.35	0.530	0.608	9.662	11.084

* From the Chemical Marketing Reporter (October 1981)

configuration greater dispersion of the tracer is expected in transport through a porous matrix than in fracture flow.

We have adapted Lenda and Zuber's method, which in its original form applies to radioactive tracers, for use with ionic tracers derived from highly dissociating salts. Briefly, the modified method estimates the mass of salt to be inyected, m, from

$$m = (\mu_{salt}/\mu_{ion})(c/c_D)\ x^2\ \phi h\ (D_x/D_y)^{-1/2} \qquad (1)$$

Where c is the minimal concentration of the anion at the maximum of the breakthrough curve which assures a proper recording of *the* whole *curve*, c_D *the* dimensionless peak concentration in the dimensionless breakthrough *curve*, x the interwell distance, ϕ the porosity and h the height of the confined aquifer, and D_x and D_y the dispersion coefficients parallel and normal to the direction of flow respectively. The dimensionless ratio (D_x/vx), where v is the mean velocity of flow in the x direction, parametrizes the breakthrough curves. Whithin the range of parameters considered c_D decreases with increasing values of (D_x/vx). Therefore, from equation (1) greater values of m correspond to higher values of (D_x/V) for a given distance. Values of $(D_x v)$ range fran a few centimeters for fine sands to about 100 m for fissured rocks (Lenda and Zuber, 1970). Thus, we adopted $(D_x/v) = 100$ m in order to obtain conservative estimates of the mass of tracer to be injected.

An extra safety factor is provided by the ratio (D_x/D_y) appearing in equation (1). For liquids, theoretical and experimental values of this ratio lie between 1 and 20 for Bodenstein numbers (= effective grain diameter × man flow velocity/coefficient of molecular diffusion) ranging from 4×10^{-1} (slow laminar flow) to 10^5 (fast turbulent flow) (Lenda and Zuber, 1970 and references therein). In *our* calculations we set &/%) = 1, effectively enhancing the safety marg of *our* estimates.

We adopted $c = c_{bck} + 10\varepsilon$, where c_{bck} is the background concentration of the anion in the reservoir fluid and ε is the resolution of the corresponding method of analysis. Standard methods of analysis adequate for the concentrations of interest here have typical resolutions of 0.02 ppm, 0.01 ppm, and 0.01 ppm for bromide, iodide, and thiocyanate respectively. The vales of c thus computed are shown in Table 3.

Taking ϕh = 1m, a typical value for the test *area*, we computed the estimates *shown* in Table 3. For convenience these results are expressed in terms of the mass of NaBr to be injected in well A-7, The greater distance of well A-8 to well A-2 results in a practically negligible ~ 15%increase of the mass of tracer to be injected over the values corresponding to A-7. The background concentrations of the tracers have a more pronounced effect in this particular case. The small amounts of thiocyanates estimated indicate the advantage of using as tracers substances that are naturally absent in the brines, and for which sensitive analysis techniques exist.

Table 3 also *shows* the relative costs of the mass to be injected for each salt considered. Not surprisingly, the smallest costs, by far, correspond to thiocyanates. Note also that the relatively low background concentration of iodide compensates for its higher price per unit mass.

Although thiocyanates look very attractive from the pint of view of their low costs, they have not been extensively tested in geothermal environments. Bromide and iodide are better known as geothermal tracers, and their costs are reasonable for the planned test (US $1009 for NaBr in A-7). Therefore, we conclude that bromide and iodide are the indicated tracers for the first test in Los Azufres.

Finally, a usefull extension of *this* work is suggested *by* our results. We propose to conduct a field experiment to evaluate thiocyanate a5 a geothermal tracer. The experiment would consist of injecting this anion in parallel with the main tracers in wells A-7 or A-8. Comparison of the corresponding breakthrough curves would provide valuable information about the characteristics of thiocyanate as a geothermal tracer.

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