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A COMPARISON OF TWO MULTIPLE-TRACER TESTS CONDUCTED AT THE GEYSERS

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ABSTRACT

Two multiple-tracer tests were conducted at The Geysers to evaluate the relative properties of various gas tracers with respect to tritiated water. In this study the geographic distribution of the tracer responses in the two tests are compared. The DV-11 test, which was conducted in 1994, used the chlorofluorocarbon R-13 and SF_6. The P-1 test used the newly developed hydrofluorocarbon tracers R-134a and R-23, which are five times more soluble than those used in the DV-11 test. The hydrofluorocarbons in the P-1 test displayed similar distributions and duration of recovery to the tritium tracers. The gas tracers used in the DV-11 test, in contrast, displayed somewhat different geographic distributions and shorter recovery times than the tritium tracer. Although the results of the tests may have been biased by the higher superheat in the DV-11 area and a short-circuit to an adjacent production well, it seems clear that the hydrofluorocarbons R-134a and R-23 are superior to the chlorofluorocarbon R-13 and SF_6 as tracers in vapor-dominated systems.

INTRODUCTION

Gas tracers have been used successfully at The Geysers in more than thirty field tests (ADAMS et al., 1991; BEALL et al., 1994; BEALL et al., 1998). These tracers, defined here as tracers that are gases at room temperature and pressure, are injected as low concentration solutes in the liquid injectate, and enter the reservoir steam phase as the injectate boils. The gas tracers will always enter the steam phase at a somewhat different rate than a water-like tracer, such as tritiated water, because of their higher volatility (ADAMS, 1995; ADAMS and KILBOURN, 2000). Just how different the rate would be depends on the volatility of the tracer and the boiling parameters, such as steam velocity and mixing near the boiling interface.

Since the purpose of a tracer test is to determine where and how much water goes to which production wells, any deviation of a tracer from the behavior of water is of interest and should be examined. The best method of observing these deviations is to perform tracer tests in which gas tracers are injected along with tritiated water (hereafter referred to as tritium). Two such tests have been conducted at The Geysers, one in 1994, in Unocal's injection well DV-11 (VOGE et al., 1994), and one in 1998, in NCPA's injection well P-1 (ADAMS et al., 1999). The tests were cost-shared by DOE and industry. The tracers used in the DV-11 tests, SF_6 and R-13, are considerably less soluble than those used in the P-1 test (R-23 and R-134a). In this paper, the tests are described and compared.

DV-11 TEST

Injection into DV-11 began during September, 1993, in an area of high superheat (i.e., depletion). The test was conducted during April, 1994. One hundred curies of tritium, 0.1 kg of SF_6, and 105 kg of R-13 were injected over an eight hour period. The difference between the quantities of SF_6 and R-13 used are roughly proportional to their detection limits, 5×10^{-7} and 1×10^{-3} ppmw, respectively. Tracer was detected in twenty-seven wells. Figure 1 shows the geographic distribution of the tracer response in the DV-11 test. In this figure, which takes the form of a table, each cell represents the normalized concentration and distribution of one tracer during one day of the test. The data were normalized by dividing the measured concentrations by the injection mass (or activity in the case of tritium). Thus the data are directly comparable with respect to dilution from a point source. Even though the range of normalized concentrations for the various tracers were similar within one or two orders of magnitude, the same bin ranges were not used for each tracer in order to preserve the differences between them.

All of the tracers were found in wells near the injection well on day 0, which was the day the tracers were injected. Tritium had the largest measured response, primarily because of the sizable quantity injected. The tritium amount was based on Unocal's prior experience with less depleted reservoirs, which required an order of magnitude more tracer than the current state of the reservoir.

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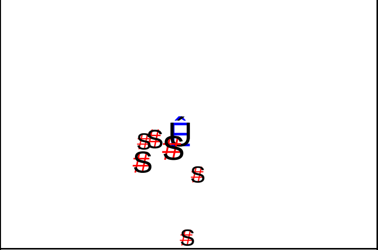
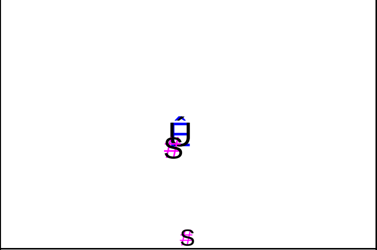
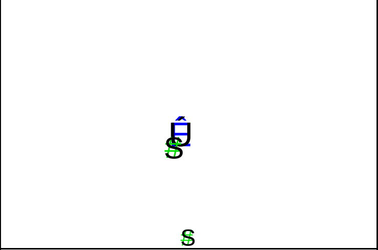
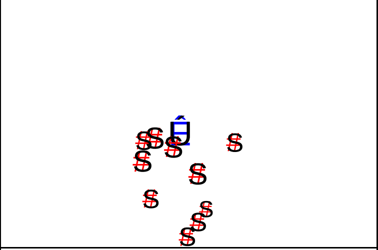
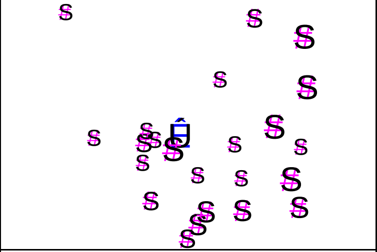
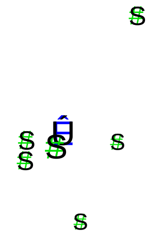
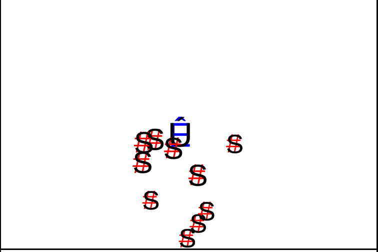
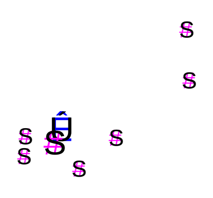
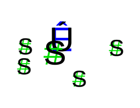
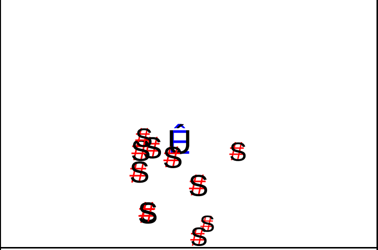
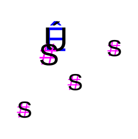
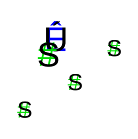
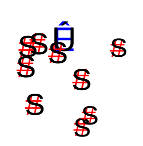
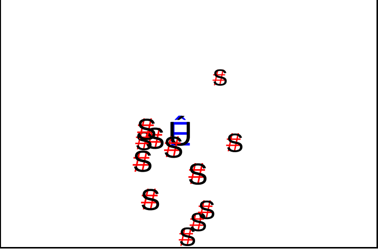
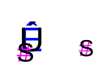
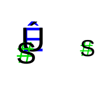
0			
1			
2			
4			
9			
11			

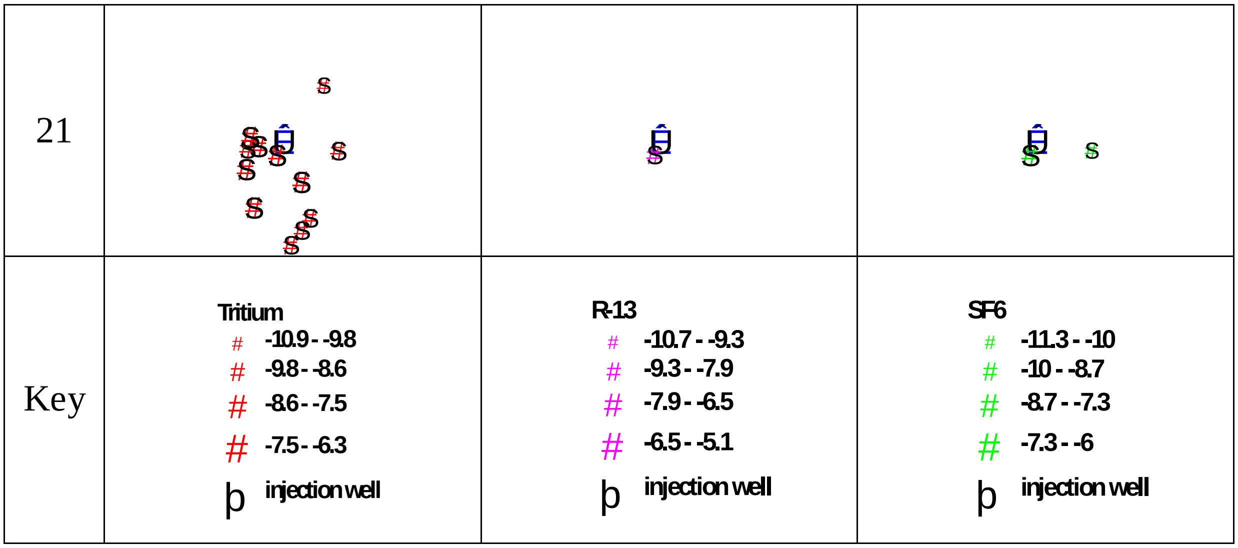


Figure 1. Log of the normalized tracer concentrations for each day of the DV-11 tracer test. Each cell in the "table" is a map of the test area showing the magnitude of tracer response at the center-of-steam location for each well. Each column is for one tracer, and each row is the day of the test specified in the leftmost column. The log of the normalized concentration range of each tracer throughout the test was divided into four sub-ranges, shown by the four sizes of filled circles. The data were normalized by dividing the measured concentrations by the injection mass, using the same mass or activity units. Thus the data are directly comparable with respect to dilution from a point source.

On day 1, the gas tracers showed the largest response of the entire tracer test. The tritium response on day 1 also increased, but tritium concentrations continued to remain high throughout the remainder of the test (21 days). In contrast, the gas tracers decreased on day 2 and were measurable in only one or two wells for the remainder of the test. The one remaining difference between the tritium and the gas tracers is that gas tracers but no tritium were detected in a well more than 1,000 feet northeast of the injection well on days 1 and 2.

The small duration of gas tracer recovery relative to tritium is consistent with the larger relative concentrations of the gas tracers during days 1 through 4. In fact, the well adjacent to the injection well (DV-12) displayed the highest concentrations of the entire test on every day that it was sampled. The proximity of DV-12 to the injection well and the large amount of superheat in the reservoir may have caused early boiling and subsequent short-circuiting of the gas tracers, resulting in a depletion of gas tracers in the steam feeding the other wells.

Although the gas tracers obviously did not show the same response as tritium, on day 1 R-13 was found in every well in which tritium was recovered on days 0 through 21. In other words, R-13 identified the same injection-production flow paths as tritium but R-13 also pointed out several other paths fed by steam from the first boiling of the injectate.

The flow rates of the wells were not available for integration of the tracer mass recovered in the DV-11 test. However, the inverse relationship between the length of the tracer recovery and the maximum concentrations may imply that a similar fraction of the injected tracer mass may have been recovered for each of the three tracers.

SF_6 STABILITY

The use of SF_6 in tracer tests subsequent to the DV-11 test has been problematic. Several laboratory experiments have been conducted on SF_6 to determine its stability at high temperatures in pure water (ADAMS et al., 2000). SF_6 has also been used successfully in field tests in liquid-dominated systems (BIXLEY et al., 1995; UPSTILL-GODDARD and WILKINS, 1995). Although these tests indicated that SF_6 should be stable in geothermal systems up to temperatures of at least 340°C, there have been several reports of problems with SF_6 during field tests in vapor-dominated systems. Calpine (Joe Beall, personal communication) and Thermochem (Paul Hirtz, personal communication) both report tests in which SF_6 did not appear in the production wells as expected. In the case of the Thermochem test, SF_6 was co-injected with R-134a and showed a strong depletion with respect to R-134a in the production returns. In contrast, the normalized concentrations of SF_6 in the DV-11 test relative to R-13 indicate that SF_6 may not have been lost (Fig. 1). However, the use of SF_6 in vapor-dominated systems is not recommended because of the problems encountered in the majority of field tests that used this tracer.

P-1 TEST

On August 18, 1998, NCPA began their multiple-tracer test by injecting 111 kg of R-134a, 93 kg of R-23, and 13 curies of tritiated water (tritium) into well P-1. Unfortunately, the gas tracers were not injected simultaneously but instead were injected back to back. However, tritium was injected continuously during the entire period of gas tracer injection, which took 3 hours. Sampling of steam from nearby production wells began the same day, and by the end of December (about 19 weeks later) 590 samples had been collected from 34 different surrounding production wells and analyzed for at least one of the tracers. However, all samples were not analyzed for all of the tracers, complicating any interpretation of the results. Detection limits of R-134a and R-23 were approximately 10^{-4} and 10^{-5} ppm by weight, respectively. Tracers were found in thirty of the thirty-one wells sampled for this test. Peak concentrations of the gas tracers ranged from the lower parts per trillion to 14 parts per million. The peak concentrations of the gas tracers were encountered as early as two days and as late as 14 days, and as late as 57 days in the case of the tritium tracer.

The results of the P-1 tracer test are presented in Figure 2. They are plotted in the same manner as Figure 1, with the exception that the log of the normalized concentrations in this case range from –10.6 to –7.3 for tritium, –12.3 to –7.0 for R-134a, and –11.9 to –7.2 for R-23.

All of the tracers appeared in the production wells at comparable concentrations on day 0. On day 1, the number of wells increased dramatically for the gas and tritium tracers. The geographic distribution of the two types of tracers was similar, with the exception that the gas tracers had a northeast component lacking in the tritium response, and the gas tracer distribution extended out somewhat further. On days 2 through 4 the geographic extent of all of the tracers expanded, with the gas tracers continuing their greater extent and northeast component. The distribution is very similar for all of the tracers on days 7 through 56, with the tritium tracer having an increased but still small component of northeast distribution. Although sampling for the gas tracers ceased on day 56, tritium sampling continued on to day 150, although only day 78 is shown here. It can be seen that the tritium began to appear further south on day 78 than at any time during the test. Similar tritium concentrations were measured in these wells through day 149 of the test.

Examination of the raw data for the P-1 test indicates that the wider distribution of the gas tracers with respect to tritium was an artifact of the sampling schedule. The gas and tritium samples were taken separately, and the same wells were not always sampled for both types of tracers. Thus, the wells that showed gas tracers but not tritium in Figure 2 are wells that were sampled only for gas tracers.

The mass recoveries of the tracers were calculated for this test, and on day 56 they were 37% for tritium, 75% for R-23, and 97% for R-134a. The recovery fraction of tritium would certainly be higher if taken out to day 149 of the test, but the flow rate data were not available at the time of writing.

COMPARISON OF DV-11 AND P-1 TESTS

The P-1 and DV-11 tests were conducted under similar conditions but with different tracers. The reservoir around the injection wells differed in that the DV-11 area had more superheat than the P-1 area. At the time of the tests, DV-11 had been in service for eight months and P-1 for 6 months. However, the P-1 region had been serviced by other injection wells for several years, and thus was less depleted.

In general, the difference between the two tests was that the P-1 tracers traveled farther and showed up in more wells than the DV-11 tracers. The narrower geographic spread of the DV-11 test is reflected in the tracer concentrations, which were higher in the DV-11 wells. With respect to the behavior of the specific tracers, a difference could be seen in both tests in the distribution of the least soluble gas tracer. In the DV-11 test, SF_6 showed up in fewer wells than R-13, and similarly, in the P-1 test, R-23 appeared in fewer wells than R-134a. However, the difference between less and more soluble tracers is much less visible in the P-1 test than the DV-11 test.

The solubility of the tracers is the property that controls their behavior in tracer tests in vapor-dominated systems. The tracers used in the DV-11 test, SF_6 and R-13, have much lower solubilities than those used in the P-1 test (Table 1). At 150°C, steam will contain approximately 75,000 times as much SF_6 as the liquid phase under equilibrium conditions, and R-13 24,000 times as much. R-23 and R-134a will fractionate to the steam by factors of 12,000 and 4,000, respectively.

Table 1. Distribution coefficients (B) of the tracers used in the DV-11 and P-1 tracer tests. B is defined as the ratio of the concentration in the steam to that in a coexisting liquid.

Temperature	**100°C**	**150°C**	**200°C**
SF6	**469469**	**75181**	**12039**
R-13	**136057**	**24004**	**4235**
R-23	**30814**	**11777**	**4501**
R-134a	**14083**	**3771**	**1010**

When the gas tracer distributions are compared to tritium, there is a definite difference between the two tests. In the DV-11 test, the only comparable distribution of R-13 to tritium is on day 1. At no time during the test was the distribution of SF_6 comparable to tritium.

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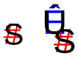
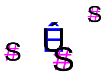
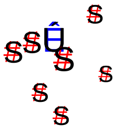
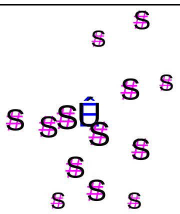
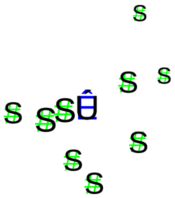
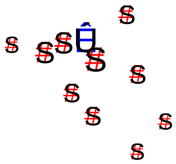
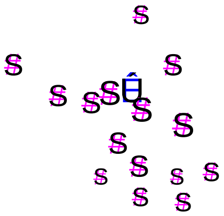
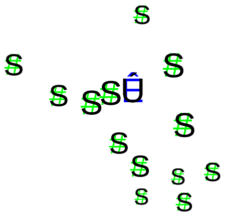
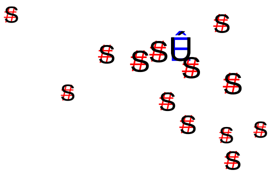
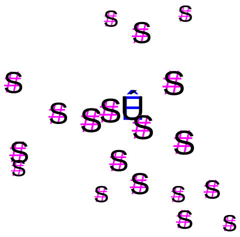
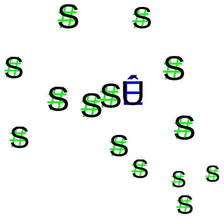
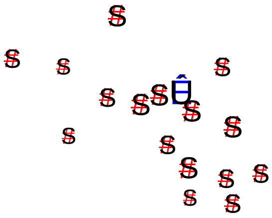
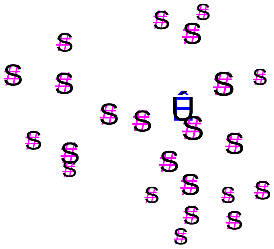
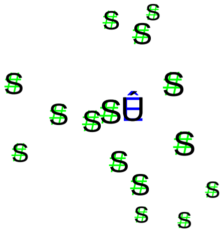
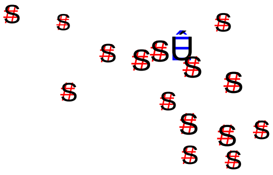
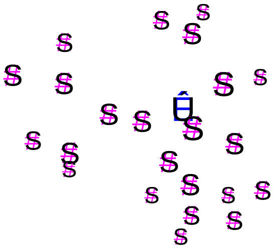
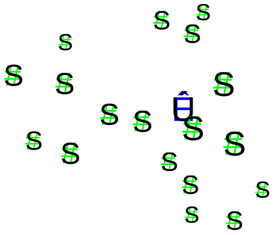
0			
1			
2			
4			
7			
9			

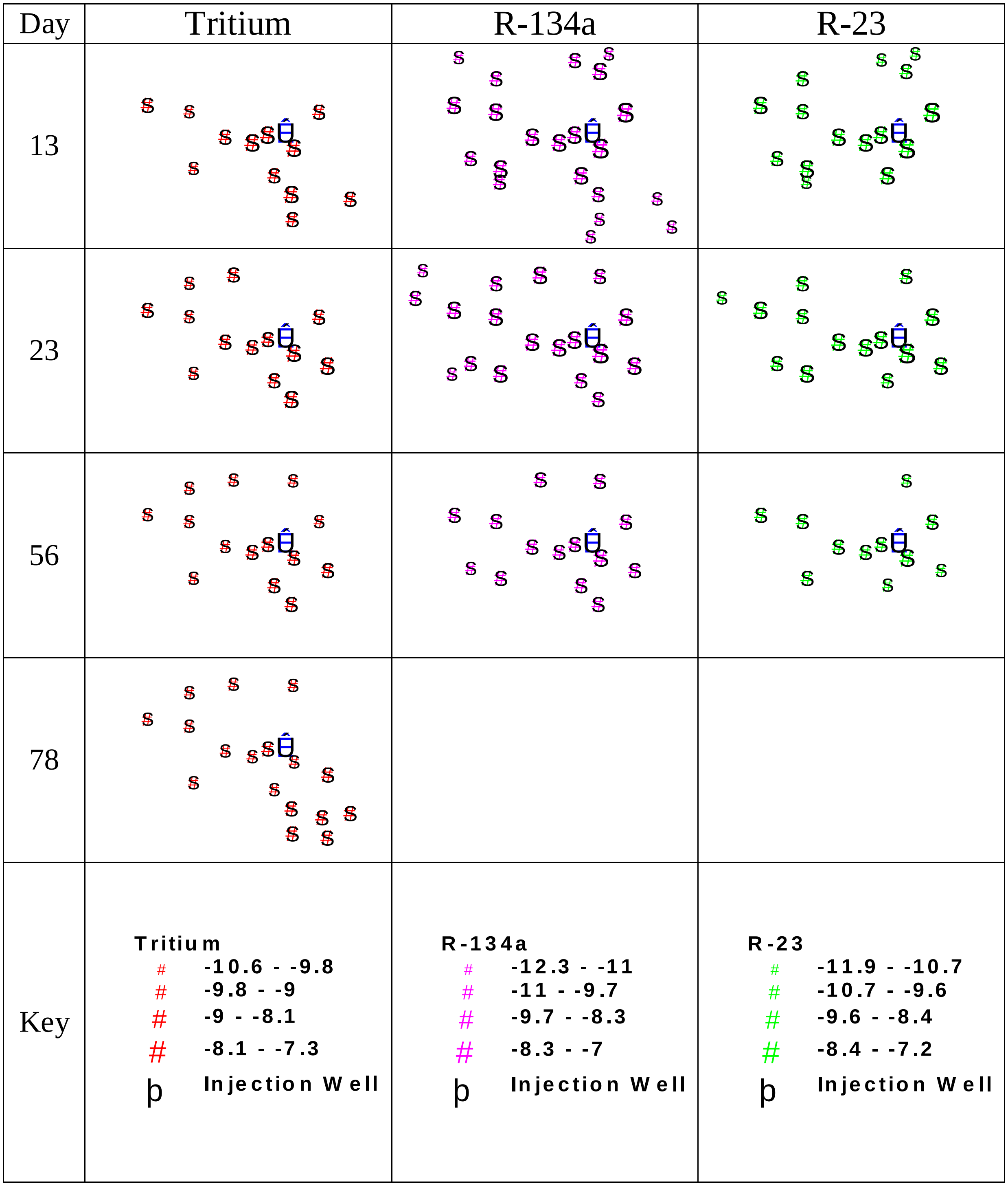


Figure 2. Log of the normalized tracer concentrations from the P-1 tracer test. Each cell in the "table" is a map of the test area showing the magnitude of tracer response. See figure 1 for explanation. Note that the apparently greater spread of the gas than the tritium tracers was due to a lack of sampling for tritium in the outlying wells.

In contrast, the geographic distribution of the gas tracers in the P-1 test contained that of tritium for the duration of the test. At the end of the test, significant quantities of tritium were recovered from the southernmost wells. A logical conclusion from these data would be that liquid injectate containing tritium but no gas tracers was flowing southward during the late stages of the test. However, gas tracers were not sampled at that time so no conclusions can be drawn on any differential behavior of the two types of tracers. Although the gas tracers showed a very similar geographic pattern to the tritium tracer, they

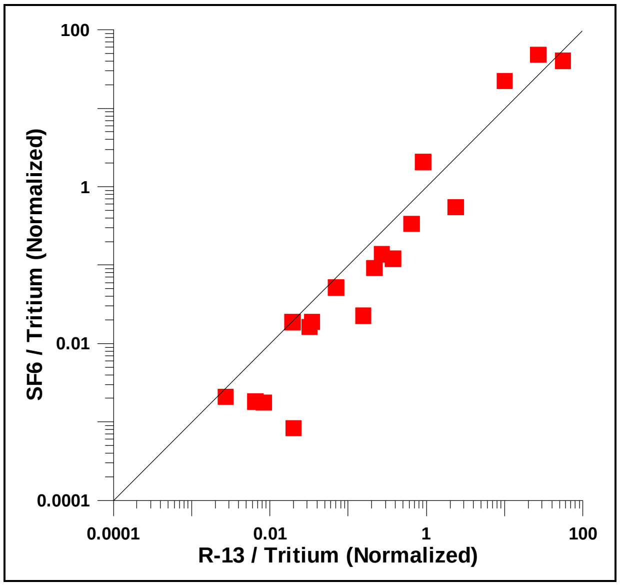


Figure 3 Normalized concentrations of the gas tracers in the DV-11 test. The line follows a one-to-one relationship. Samples which plot to the right of the line with respect to tritium are enriched (or less depleted) in the more soluble tracer than those that plot to the left. See Fig. 1 for an explanation of the normalization.

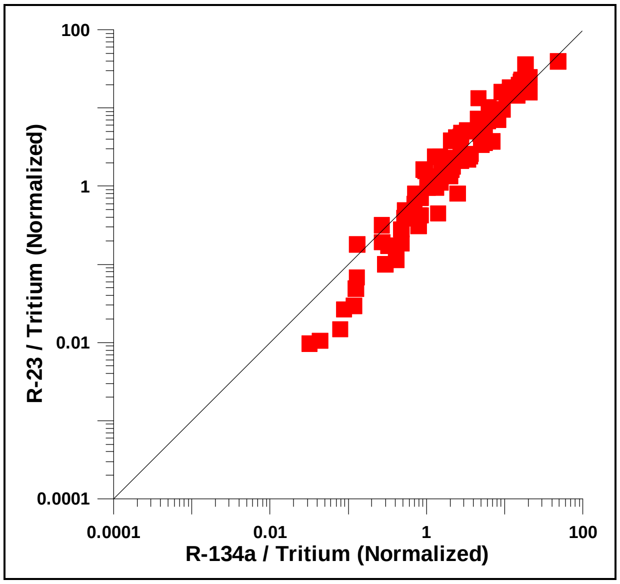


Figure 4 Normalized concentrations of the gas tracers in the P-1 test. See Fig. 3 for explanation

display concentration enrichments due to their volatility. This can be examined by plotting the ratio of the gas tracer to tritium in each sample. Figures 3 and 4 show this enrichment for each tracer used in the DV-11 and P-1 tests, respectively. It can be seen in these figures that the maximum ratios of gas tracers to tritium in the two tests were similar, ranging from 40 to 55. The minimum ratios of the two tests do show a difference, with the DV-11 tracers being a factor of ten lower then those of the P-1 test. In addition, comparison of the two plots shows that the distribution of the DV-11 samples was bimodal (Fig. 3), with those in the upper range representing strong fractionation, and those in the lower range showing weak to strong depletion. The samples showing strong fractionation are all from the well immediately adjacent to the injection well, which may have acted as a vent for the gas tracers and depleted the gas tracers from the steam before it reached the other wells. The P-1 test showed no bimodal distribution and clustered in the range of 1/100 to 45 times the respective tritium concentrations.

SUMMARY

The results of the DV-11 and P-1 tracer tests show a unique view of the different properties of gas and tritium tracers. The tests were conducted under similar conditions, but the P-1 test used hydrofluorocarbon gas tracers, which are five times more soluble than the gas tracers used in the DV-11 test. The hydrofluorocarbons and tritium in the P-1 test displayed similar distributions and duration of recovery. The gas tracers used in the DV-11 test, in contrast, displayed different geographic distributions and shorter recovery times than the tritium tracer. Although the results of the tests may have been biased by the higher superheat in the DV-11 area and a short-circuit to an adjacent production well, it seems clear that the hydrofluorocarbons R-134a and R-23 are superior to the chlorofluorocarbon R-13 and SF_6 as tracers in vapor-dominated systems.

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