PROCEEDINGS, 23rd Annual PNOC-EDC Geothermal Conference
Hotel Inter-Continental, Makati City, Philippines, March 13-14, 2002

TRACER FLOW TESTING: NEW DEVELOPMENTS IN TRACERS AND INSTRUMENTATION

P. N. **Hirtz**[1], R. J. Kunzman[1], M. L. Broaddus[2], J. A. Barbitta[1]

[1]Thermochem, Inc., Santa Rosa, CA, USA,
[2]PT Thermochem Indonesia, Bandung, Indonesia

ABSTRACT

The chemical tracer flow test (TFT) technque for two-phase mass flow rate measurement has been in use since 1992 and is now employed routinely in the major geothermal fields of 6 countries. There have been continuous refinements in the TFT process over time, including introduction of new vapor and liquid tracers, and upgraded tracer metering equipment. Since F T is now used by many operators around the world, it is important to ensure that the technique is consistent and robust, and not site-specific or sensitive to small deviations in methodology. Comparative data are presented for some of the various tracers, including recent tests on alcohol tracers. These tests show sulfur hexafluoride (SF_6) is the most versatile and accurate tracer for F T steam measurements, while alcohol can be used in limited applications. Sodium benzoate was until recently the primary liquid-phase tracer, but is now being replaced by polyaromatic sulfonate (PAS) tracers. The SF_6 and PAS tracers allow miniaturization of the tracer metering equipment, resulting in greater portability and lower cost.

1.0 INTRODUCTION

In two-phase geothermal fields, monitoring the enthalpy of produced fluids is important in understanding the reservoir performance. Decreasing enthalpy can indicate breakthrough of injection water or invasion of cooler groundwater, while increasing enthalpy can indicate reservoir boiling and the formation of a steam cap. Enthalpy is essential for the interpretation of geochemical data because it determines the steam fraction at sampling conditions and allows the correction of chemical concentrations back to reservoir conditions. Enthalpy and mass flow rate govern the amount of steam available from each well and ultimately the energy output of the power plant.

Mass flow rate of steam and water phases and total enthalpy of the flow can be measured directly for individual geothermal wells that produce to dedicated separators. However, due to the high capital cost of production separators, most geothermal fluid gathering systems are designed with satellite separation stations in which several wells produce to a single separator. In many cases all of the two-phase fluids produced from a field are combined by the gathering system and separated in a large vessel at the power plant. Without dedicated production separators for each well, the steam and water mass flow rates and total enthalpy of individual wells cannot be measured during production.

Well testing with an atmospheric separator, James Tube and weir box can provide reasonably accurate enthalpy and mass flow rate values (James, 1970). However, this method requires diversion of flow from the power plant, with subsequent revenue losses. In some fields atmospheric venting of steam may not be allowed due to environmental regulations for hydrogen sulfide emissions and brine carry-over.

The injection of chemical tracers into two-phase flow allows the determination of steam and water mass flow rates directly from tracer concentrations and tracer injection rates without disrupting the normal production conditions of the well. There are currently no other on-line two-phase flow metering systems available for geothermal applications, but testing of a vortex shedding flowmeter (VFM) with a dielectric steam quality Sensor (DSQS) was performed at the Okuaizu field, Japan, in October, 1998 (Yasuda *et al.,* 2000). The VFM/DSQS system was calibrated against the TFT method, and two of the three tests agreed within 10%. The DSQS is sensitive to liquid and vapor phase electrical conductivity, so large corrections are required for dissolved salts in brine and noncondensable gases (NCG) in steam. It was also concluded that the Sensors would be adversely affected by scale deposition if used in continuous operation.

2.0 THEORY OF THE TFT METHOD

The tracer flow test technique requires precisely metered rates of liquid- and vapor-phase tracers injected into the two-phase flow stream. Samples of each phase are collected with sampling separators at a location far enough downstream of the injection point to ensure complete mixing of the tracers in their respective phases. The water and steam samples are analyzed for tracer content, and the mass flow rate of each phase is calculated based on these measured concentrations and the injection rate of each tracer.

The mass rate of liquid (Q_L) and steam (Q_V) is given by:

$$Q_{L,V} = Q_T / C_T \qquad (1)$$

where:

$Q_{L,V}$ = Mass Rate of Fluid (liquid or steam)
Q_T = Tracer Injection Mass Rate
C_T = Tracer Concentration by Weight

The mass rates calculated for each phase are valid for the temperature and pressure at the sample collection point. The total fluid enthalpy can then be calculated from a heat and mass balance equation using the known enthalpies of pure liquid and steam at the sample collection pressure/temperature. Enthalpy corrections can be made for high-salinity brine and high-NCG steam if necessary.

3.0 TRACER SELECTION CRITERIA

Selection criteria for liquid- and vapor-phase tracers, techniques for metering and injection of tracers, procedures for two-phase sampling, and precision and accuracy of the method are discussed in detail by Hirtz et *al.* (1993). In summary, the selection of liquid- and vapor-phase tracers for the TFT technique must be based on an evaluation that includes the following considerations:

- Each tracer must partition completely into its respective phase (vapor or liquid).
- The tracers must be thermally and chemically stable under the conditions of two-phase geothermal production, and non-reactive with chemical constituents in the steam or brine.
- The liquid-phase tracer must be highly soluble in water so that concentrated solutions can be prepared.
- The gas-phase tracer must have a high vapor pressure to facilitate injection and metering.
- Quantitative, highly precise analytical methods with wide linear ranges must be available to measure the tracers in a geothermal fluid matrix.
- Natural background of the tracers should not exist or concentrations should be relatively low and stable.
- The tracers should not also be used for reservoir tracer applications in the same geothermal field.
- The cost of the tracers must be reasonable for the quantities to be injected.

4.0 TRACER EVALUATIONS AND COMPARISONS

The liquid-phase tracers that have been evaluated by Thermochem to date are:

- Fluoride (as KF)
- Bromide (as NaBr)
- Fluorescein dye
- Sodium benzoate
- Rhodamine WT dye
- 1,5-naphthalene disulfonate
- 2,7-naphthalene disulfonate
- Polyaromatic sulfonates (proprietary)

Bromide and benzoate have been the most widely used and are considered reference tracers because they have been extensively validated against conventional flowmeters (Hirtz et *al.*, 1993; Hirtz and Lovekin 1995). Benzoate and the polyaromatic sulfonate (PAS) tracers meet all the selection criteria. The naphthalene disutfonate tracers meet all criteria except routine use as reservoir tracers. The other tracers meet most of the selection criteria, but fluoride can precipitate as fluorite (CaF_2), and rhodamine WT may be adsorbed by silica scales and precipitates. Bromide and fluoride have natural background levels that are relatively low and constant in most fields. All the tracers can be made as solutions of **30%** by weight or more and are not excessively expensive.

The vapor-phase tracers that have been evaluated by Thermochem are:

- Propane
- Sulfur hexafluoride (SF_6)
- Freon-12
- Helium
- Isopropanol

The first four vapor-phase tracers listed are injected as gases. The gas tracers are all available in high-pressure cylinders of 140 bar or more and can be accurately metered using thermal mass flow control technology. Isopropanol must be injected as a liquid using a high-pressure metering pump. Propane and SF_6 have been the most widely used vapor-phase tracers and are considered reference gas tracers due to numerous validation tests conducted with high-accuracy steam flowmeters (Hirtz et *al.*, 1993; Hirtz and Lovekin 1995). Propane and helium have natural background levels that may be too high for practical use in some cases. Freon-I2 has exhibited thermal decay in TFT comparison tests with reference gas tracers and is not suitable. Isopropanol does not partition completely into the vapor phase, and has a significant liquid-phase solubility requiring correction. Isopropanol also requires long mixing runs compared to the gas tracers and exhibits some losses or incomplete mixing when used on wells with high brine fractions, resulting in erroneously high steam flow rates.

Fluoride was the original liquid-phase tracer validated for the TFT method (Hirtz et *al.*, 1993), but it was discontinued early-on due to concerns about fluorite precipitation. Bromide was then used for the next 2 to 3 years after a high-precision analytical method was developed. In most geothermal fields bromide levels in brine are only a few ppm, *so* background is not a problem when tracer concentrations are 100 ppm or more. However, at the Salton Sea geothermal field in California, bromide can be several hundred ppm in the hypersaline brine. The first TFT validations and routine measurements at the Salton Sea used bromide as the liquid tracer, and in spite of the high background the technique was still accurate. High volumes of tracer, numerous background samples, and very precise analytical measurements were required. Data from one of the first validation tests is given in Table 1. For this test, the background bromide level was 70% of the steady-state concentration during tracer injection.

Tabte 1. TFT comparison test results **between** bromide tracer and orifice meter at the Salton Sea, September 1993.

Injection Rate	Average Bromide, ppm		Brine Mass Flow Rate, kg/s	
37% Br, kg/min	Background	During injection	TFT	Orifice Meter
2.20	233	327	145	147

Due to the large volumes of bromide required for Salton Sea TFT, fluorescein was later substituted after some analytical problems were resolved. The technique involved collection of brine samples in sodium carbonate solutions to precipitate heavy metals and stabilize the pH. Samples had to be shielded from light to prevent photo-decay and centrifuged to separate solids. Fluorescein did not require background correction, and tracer injection rates were at least 10 times lower than bromide. Later, benzoate replaced fluorescein because it did not require special sample handling, and injection rates were in the same range. Table 2 lists the initial comparative results for fluorescein and benzoate, which agree within 2%.

Table 2. TFT comparison test results between fluorescein and benzoate tracers at the Salton Sea, July 1995.

Tracer	Injection Rate, kg/min	Tracer Conc., ppm	Brine Mass Flow Rate, kg/s
10.9% Fluorescein			
28.3% Benzoate	0.13	15.9	39.3

Rhodamine WT dye was evaluated at the Coso geothermal field in California as an alternative to bromide, before sodium benzoate was introduced. Fluorescein could not be used at Coso because it was routinely employed as a reservoir tracer, and the two applications would interfere. Rhodamine WT has as tendency to adsorb onto silica solids (Rose and Adams, 1994), so samples were diluted in the field to prevent silica polymerization. Table 3 lists the results of comparative tests between Rhodamine WT and bromide on two wells at Coso, which each agree within 1%.

A chlorofluorocarbon, Freon-12 (Cl_2F_2C), was tested at Coso as a substitute for propane in late 1993. Freon-12 can be detected in the low parts-per-trillion range and has no natural background, so it would require much lower injection rates than propane. Freon-12 was evaluated as a reservoir tracer during the first vapor-phase tracer tests at The Geysers, but it exhibited substantial decay in the reservoir (Adams et *al.*, 1991). It was then considered for TFT use because it was not suitable for reservoir tracer applications, so there would be no potential for interference. Table 4 lists the comparative results of Freon-12 and propane for two well tests at Coso. The Freon-12 derived steam rates are about 25% higher than the propane derived rates, indicating that Freon-12 decayed significantly even under the short residence time and relatively low temperature (170 °C) of the TFT process. SF_6 was later selected because it had the benefits of Freon-l2 in terms of sensitivity, lack of background, and limited reservoir use, but it had the required high thermal and chemical stability.

Table 5 lists the initial validation test results for propane and SF_6 at the Salton Sea. These tests were conducted on two wells with dedicated production separators and orifice meters that had been recently cleaned and calibrated. The SF_6 results agree with the orifice meter to within 2%. Subsequently, SF_6 has been used as the TFT vapor-phase tracer for the past 8 years. SF_6 meets all the properties of the tracer selection criteria: it has very low solubility in water (about the same as N_2) and does not require any correction for partitioning; it has no known reactivity to constituents in the geothermal fluid, it is thermally stable to 300 °C (Adams et ai., 2000); it is available as a high-pressure gas mixture up to about 8% by volume; and it can be metered precisely by a solid-state electronic mass flow meter. There is no natural background for SF_6, and it is no longer used as a reservoir tracer. SF_6 can be analyzed by common lab instrumentation, a gas chromatograph (GC) with electron capture detector (ECD), and the same gas inlet system as used for routine geothermal gas analysis. The typical concentration range for TFT measurement is 0.001 to 1 ppm, and the analytical precision is +/- 1 to 2% or better.

Tracer	Injection Rate, kg/min	Tracer Conc., pprn	Brine Mass **Flow** Rate, *kgls*
24.2% Na- Bromide			
11.1% Rhodamine WT	0.1037	111	41.8
		5.82	42.1
24.1% Na- Bromide	0.626	234	11.3
12.7% Rhodamine WT	0.047	8.73	11.5

Tracer	Injection Rate, slpm[1]	Tracer Conc., ppm	Brine Mass **Flow** Rate, kg/s
2.9% Propane	14.9	0.888	16.1
2.0% Freon-12	5.10	0.454	20.3
2.9% Propane	14.9	1.22	11.7
2.0% Freon-12	5.10	0.645	14.3

'slpm = standard liters per minute (gas at STP: 0° C, 1 atm)

Table **5.** TFT comparison test results between propane, SF_6 and orifice meters at the **Salton** Sea.

		Injection Rate, slpm[1]	Tracer Conc., ppm	Steam Mass Flow Rate, kg/s	
Tracer	Date			TFT	Orifice Meter
2.9% Propane	Sept, 1993	14.8	0.688	20.7	21.5
0.58% SF_6	Mar, 1994	1.93	0.0607	18.2	18.4
0.50% SF_6	Jun, 1994	1.89	0.0463	22.1	22.1
0.50% SF_6	Sept, 1994	1.99	0.106	10.1	10.4

Once SF_6 had been validated against conventional orifice flowmeters of known accuracy, it was used to check other differential-producing flowmeters, such as V-Cones and Annubars, in applications where the flowmeter calibration or installation was suspect and needed verification. V-Cones are installed in

Table 6. Comparative test data for TFT and Spool-Type V-Cone flow rate measurements at coso.

	Steam Flow, kg/s		
Location	SF_6 Tracer	V-Cone	Ratio
Inter-tie 7/8/95	8.57	8.69	1.01
Inter-tie 7/8/95	27.3	26.0	0.95
Unit 1 LP 6/22/95	6.8	7.2	1.06
Unit 2 LP 6/21/95	10.1	10.3	1.03
Unit 3 LP 6/22/95	10.0	10.2	1.03
Unit 7 LP 7/31/95	19.8	20.0	1.01
Unit 1 HP 6/21/95	67.8	65.5	0.97
Unit 2 HP 6/21/95	68.0	67.9	1.00
Unit 3 HP 6/21/95	66.9	67.5	1.01

pipelines to measure static and downstream pressure after the cone element; Annubars are inserted into pipelines to measure static and total pressure. Table 6 shows the results of such a test at Coso where TFT was used to check V-Cone fiowmeters installed at several power plant high-pressure (HP) and low-pressure (LP) steam lines, and at inter-ties in the steam gathering system. These particular V-Cones were complete factory assemblies installed as pipeline spool pieces. Overall, the agreement was very good, and the meters were considered to be properly installed and calibrated.

Table 7 lists the test results for insertion-type V-Cones that were field-fitted as an insertion piece through the side of the pipelines. The V-Cone flow rates were consistently lower than the TFT rates. The error was attributed to the installation, which caused a flow disturbance in the pipeline and deviations in the static pressure readings. The insertion-type V-Cones were removed and replaced with the spool-type at the manufacturer's expense.

Alcohols have been proposed as alternate tracers for TFT (Lovelock, 1997; Lovelock and Stowell, 2000) and are being evaluated as reservoir tracers (Adams, 1995). Light alcohols (C2 - C4) are attractive as vapor-phase reservoir tracers due to their high solubility in water, resulting in a vapor/liquid distribution that is much closer to unity than the gas tracers. As TFT tracers, the water solubility of alcohols is not desirable and results in significant errors if unaccounted for. In the temperature range of the TFT process, the vapor-to-liquid concentration ratio (distribution coefficient) of isopropanol (IPA) is between 10 and 20 to 1, equating to a partitioning of up to 30% to the liquid phase for fiuids with a steam fraction of 20%. This requires that the brine flow rate be measured at the same time as the steam rate, and that brine samples be analyzed for both the liquid- and vapor-phase tracers. Errors in the brine measurements are propagated to the steam measurement. For example, Agamata-Lu (2000) reported an error of almost 25% in an alcohol-TFT steam flow rate measurement at the Broadlands-Ohaaki field (well Br-20) in New Zealand, which was attributed to an error in the alcohol measurement of brine.

Table 7. Comparative test data for TFT and insertion-Type V-Cone flow rate measurements at Coso.

	Steam Flow, kg/s		
Location	SF_6 Tracer	V-Cone	Ratio
Unit 5 LP 6/9/95	150	126	0.84
Unit 5 LP 8/15/95	172	149	0.87
Unit 6 LP 7/8/95	123	108	0.88
Unit 6 LP 8/15/95	150	127	0.85
Unit 8 LP 6/9/95	163	97	0.60
Unit 5 HP 6/9/95	549	476	0.87
Unit 5 HP 7/9/95	569	496	0.87
Unit 5 HP 8/15/95	516	486	0.94
Unit 6 HP 7/8/95	559	506	0.91
Unit6 HP 8/15/95	523	468	0.89

Aside from complications due to water solubility, there are several potential chemical reactivity problems in the alcohol-TFT process. Alcohols are known to react with boric acid and silicic acid, both of which are ubiquitous in geothennal steam and brine, forming borines and silicon esters by the following reactions:

Alcohol and Boric Acid:

$$3\,ROH + B(OH)_3 \rightarrow B(OR)_3 + 3\,H_2O \tag{2}$$

Alcohol and Silicic Acid:

$$4\,ROH + Si(OH)_4 \rightarrow Si(OR)_4 + 4\,H_2O \tag{3}$$

The "R" represents the hydrocarbon component of each species. These reactions can theoretically consume 3 to 4 moles of alcohol per mole boron or silica. A US patent has been filed on this process as a means to remove boron and silica from geothermal steam by injecting an alcohol solution into the steam flow, in the same manner as proposed for alcohol-TFT (Gallup, 1998). These reactions would occur in a liquid phase, where boric acid and silicic acid concentrations are highest, and probably do not occur to any extent directly in the vapor phase.

Tracer	Injection Rate'	Steam Conc., ppm	Brine Conc., ppm	Steam Fraction, Yo	Steam Mass Flow Rate, kg/s
1.00% SF_6	0.495 slpm	0.0280	< 0.0001	21.1	19.2
37.2% IPA	0.401 kg/min	89.6	5.04		25.0
1.00% SF_6	0.498 slpm	0.0219	< 0.0001	18.9	24.7
54.7% IPA	0.400 kg/min	110.2	5.70		29.7
1.00% SF_6	0.498 slpm	0.0214	< 0.0001	16.4	25.2
53.8% IPA	0.403 kg/min	96.2	5.45		32.5

Tracer	Injection Rate'	Steam Conc., ppm	Brine Conc., ppm	Steam Fraction, Yo	Steam Mass Flow Rate, kg/s
5.00% SF_6	0.100 slpm	0.0826	< 0.0001	16.0	6.58
36.9% IPA	0.260 kg/min	182.5	10.4		8.04

Another potential problem with alcohol-TFT is the reaction between alcohol and the liquid-phase tracer, sodium benzoate. The Fischer Esterfication reaction proceeds as,

Alcohol and Benzoate:

$$ROH + (C_6H_6)COO^- + H^+ \rightarrow (C_6H_6)COOR + H_2O \qquad (4)$$

forming an ester from the alcohol and benzoate. This reaction is catalyzed by acidic conditions, so it is not likely to proceed to a significant degree in a mixture of alcohol and sodium benzoate (alkaline). The reaction could be significant if benzoic acid is used rather than benzoate, or if the brine pH is low.

Field trials using isopropanol and sodium benzoate for TFT were conducted by Thermochem at the Salak field, Indonesia, and the Coso field, California. Table 8 lists the comparative results between SF_6 and IPA for three wells at Salak. The IPA-derived steam rates are 20 to 30% higher than the SF_6-derived rates, indicating loss of IPA due to chemical reaction or incomplete vapor/liquid mixing and equilibrium. The reactions discussed above are possible sources for error, as boron, silica and benzoate were all present in the geothermal fluids. The brine pH is neutral to alkaline, so IPA/benzoate esterfication in the brine is unlikely, but borine and silicon ester formation is possible.

These tests were conducted on wells with steam fractions of 20% or less, which are lower than previously published data for alcohol-TFT by Lovelock (1997, 2000). The initial evaluations of the TFT process included studies on tracer mixing requirements versus steam fraction (Hirtz et *al.*, 1993). It was found that fluids with high brine fractions require much longer mixing runs due to the flow regime, which tends towards slug or stratified flow under these conditions. It is possible the Salak alcohol-TFT tests suffered from incomplete mixing and phase distribution. During injection of the alcohol-benzoate solution, several steps must occur before the alcohol tracer achieves equilibrium distribution and complete mixing in each phase: the solution must be heated to the process temperature; the pure solution must boil; any solution that immediately dissolves in the brine must exsolve alcohol and the vapor must mix with the steam phase; any excess alcohol in the steam must dissolve back into the brine; and so on. In other words, a multi-stage process must occur with varying iterations of mass transfer between phases depending on the flow regime and the physical injection point of the tracer within that flow. This, of course, takes time and distance along the pipeline. In contrast, the SF_6 vapor tracer is injected as a gas, and needs only to physically disperse in the steam phase.

Additional IPA tests were conducted at Coso after the Salak tests to further investigate the discrepancy in IPA results. Table 9 shows the results of a comparison between SF_6 and IPA on a well with a standard 30-meter mixing run and 16% steam fraction. Again the IPA-derived steam rate is high by over 20%.

Tracer	Injection Rate'	Steam Conc., ppm	Brine Conc., ppm	Steam Fraction, %	Steam Mass Flow Rate, kg/s
5.00% SF_6	0.100 slpm	0.0884 ppm	< 0.0001, ppm	95.3	6.14
61.2% IPA	0.215 kg/min	164.5 ppm	31.5 ppm		13.4
5.00% SF_6	0.100 slpm	0.0893 ppm	< 0.0001 ppm	95.3	6.07
61.296 IPA	0.220 kg/min	369.9 ppm	22.0 ppm		6.07

A series of tests were then conducted on the Same well at Coso used for the initial tracer mixing evaluations 10 years ago. Table 10 lists the results for tests where the SF_6 and IPA/benzoate solution were injected 5 meters upstream of the sample point and again at 50 meters upstream. The IPA steam rate is high by 120% for the 5-meter run, demonstrating poor mixing, even though the steam fraction for this well is 95%. Non-equilibrium distribution and incomplete vaporiiation are indicated by the high brine concentration of IPA (distribution ratio of 5, compared to 10 - 20 for equilibrium).

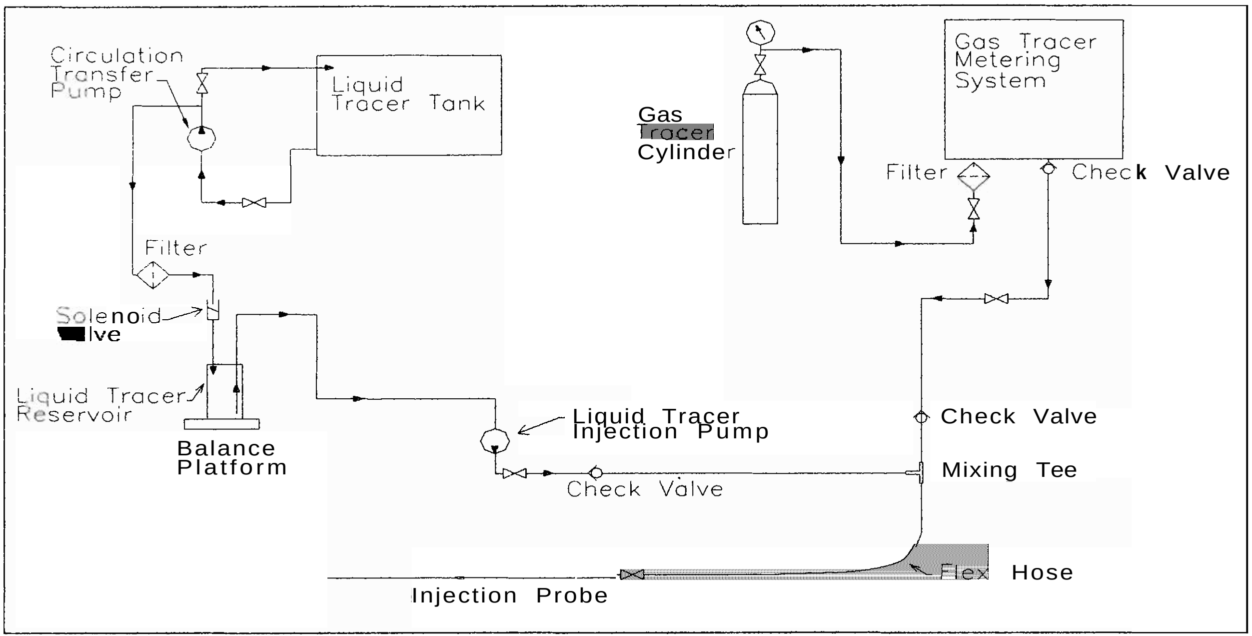
The results for the 50-meter mixing run show that IPA can work as a vapor-phase tracer under specific, ideal conditions. With a long mixing run and high steam fraction, the SF_6 and IPA-derived steam rates agree exactly. The SF_6 rate for both injection locations agree within 1%, demonstrating the robustness of SF_6 as a vapor tracer.

A similar trend in alcohol-TFT error versus steam fraction was observed in tests conducted by Agamata-Lu (2000) in the Broadlands-0haaki field. Although the tests cannot be considered validation tests because they were compared to James-Tube measurements made three months earlier, they do indicate errors in steam flow of several hundred percent for wells with steam fractions of 12% (wells Br-20, Br-25), and an error of only 5% for a well with a steam fraction of 18% (Br-8). In all cases the alcohol-TFT flow rates were high, suggesting alcohol loss or incomplete mixing and phase distribution. The latter seems unlikely, since the distance between the injection and sampling points was 100 meters. Therefore, Alcohol-TFT may suffer from both mixing limitations in short piping runs and chemical reactions in long runs with high brine fractions. Significantly more of the total alcohol is dissolved in brine when the brine fraction is high, and the reaction time is greater for long mixing runs, so these conditions would be ideal for chemical reactions that occur in the liquid phase, such as the formation of borines and silicon esters.

Another concern with alcohols as TFT tracers is analytical precision. The IPA samples from the Salak and Coso tests were collected at temperatures below 25 °C in gas-tight glass vials as a precaution against loss of alcohol, which is volatile. The analyses were performed by direct injection onto a GC with Flame Ionization Detector (FID). The relative standard deviation (RSD) for each group of 6 samples per test ranged from 5 to 14%, while the RSD of SF_6 analyses conducted for the same tests were all 1% or less. The poor precision is the result of the direct injection technique, where small micro-liter quantities of sample are injected with a syringe onto the GC column. Good accuracy can be obtained with numerous repeat injections because the error is random, but this is not an efficient means of analysis. Previously published results for alcohol-TFT (Lovelock, 2000) used automated headspace gas analysis provided by a forensic laboratory. This equipment is considerably more expensive than the GC/ECD used for SF_6 analysis, but it appears to be required for high-precision alcohol analyses.

5.0 TRACER METERING TECHNOLOGY

The TFT technique relies upon accurate and precise metering of the liquid- and vapor-phase tracers injected into the two-phase flow stream. Mass flow rate measurement devices were chosen as the best means to meter the tracers without errors related to density and viscosity corrections for gas and liquid over a wide range of operating temperatures. Constant injection rates are also necessary to minimize errors and



'igure 1. Schematic of the MaxiSkid and MiniSkid.

data reduction complications associated with the time delay between injection of tracer and subsequent recovery by sampling downstream. Several developments in metering equipment have been made since inception of TFT, although the fundamental principles have remained the same.

The original TFT equipment package was designed to be used under a wide range of process and climatic conditions. The equipment also had to withstand routine use; up to 65 wells tested per field every 3 months (Coso). Since the bromide and propane tracers required high injection rates, the first equipment was bulky and needed to be skid-mounted. With the introduction of benzoate and SF_6 tracers, equipment size was reduced substantially, but was still skid-mounted. A general schematic for these tracer injection systems, termed MaxiSkid and MiniSkid, is shown in Figure 1. A total of 12 systems of this type are currently in use in the USA, the Philippines, Japan, Indonesia and Iceland.

The liquid-tracer metering for these systems is by a high-precision positive-displacement pump, relatively insensitive to discharge pressure fluctuations, operating at a high stroke frequency in conjunction with a pulsation damper to effectively produce a continuous flow stream. The true mass-injection rate of the liquid tracer is monitored by an electronic balance interfaced to a portable computer. The metering pump draws from a reservoir placed on the balance, which measures the weight loss continuously during injection. The computer records the weight-loss data versus time and calculates the mass-injection rate over selected intervals, along with running averages and cumulative totals. Although the stroke setting of the metering pump usually provides reproducible injection rates, monitoring true mass delivery results in the highest possible accuracy, typically better than +/- 0.1%. Without the weight-monitoring system, the injection-rate accuracy can suffer from changes in pump output due to fluctuations in voltage, friction, fluid compressibility, etc.

A mass-flow-based system is also used for gas-tracer metering. The motive force for gas-tracer injection is from the high-pressure gas cylinder itself. An electronic mass-flow controller (MFC) regulates the gas flow rate with high precision by sensing the cooling of an integral heated coil exposed to the flowing gas. This cooling effect is proportional to the mass flow rate of the gas. A solenoid metering valve is continuously adjusted by the control unit to maintain the gas flow at the desired set-point, within at least +/- 1%.This is a standard laboratory and industrial device for high-accuracy gas metering, with special modifications to accommodate the high delivery pressure and the cycling caused by pressure surges in the two-phase line.

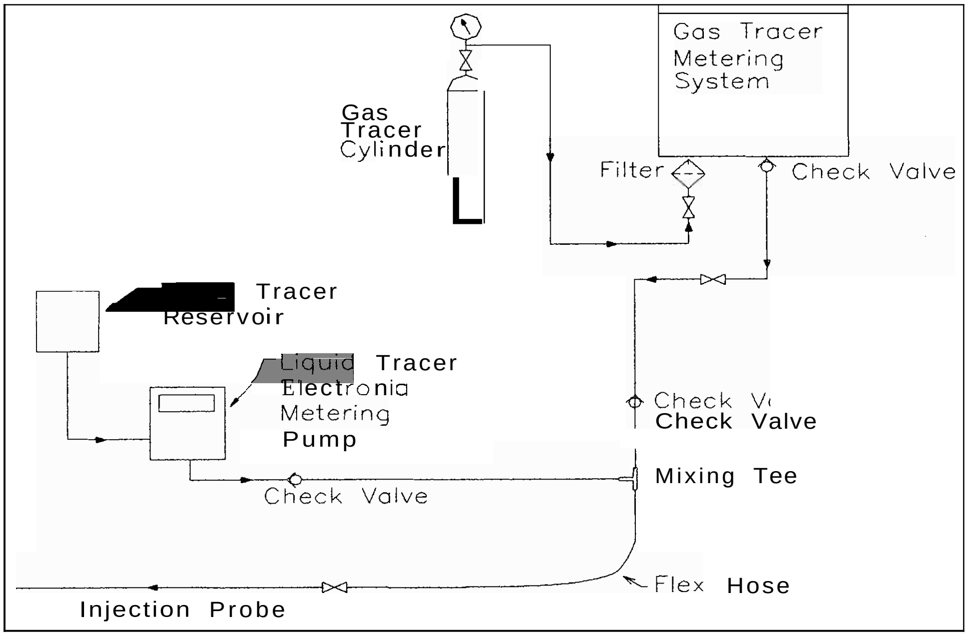


Figure 2. Schematic of the MicroMod unit

The liquid and gas tracers are co-injected through a stainless-steel probe inserted into the two-phase flow line near the wellhead. A probe is used to eliminate any possible leakage of tracer from the sample-port valve packing or related connections, and to deliver the tracers directly into the flow stream. Although the gas and liquid tracers are co-injected, they are entirely independent in terms of metering, sampling and analysis. Therefore, there is no propagation of errors between the steam and brine measurements. If there is an error in the measurement of one phase, it is often detectable by evaluation of the total enthalpy. Steam and brine rates can also be measured independently, either for single-phase or two-phase flow streams. These advantages do not exist when the vapor and liquid tracer are injected by the same metering system, as is the case for alcohol tracers mixed with benzoate.

The introduction of polyaromatic sulfonate (PAS) liquid tracers and availability of a new generation of liquid micro-metering equipment have allowed the recent miniaturization of the liquid-tracer metering system. At the same time, the MFC has been miniaturized, resulting in reductions in tracer injection rates by one or two orders of magnitude. The PAS tracer analysis is very sensitive and has a linear range of at least 0.005 to 0.5 ppm in brine. This range is 3 orders of magnitude lower than sodium benzoate. Due to the very high sensitivity of SF_6 analysis by GC/ECD and the ability to increase the tracer mixture concentration up to about 8% by volume, the SF_6 injection rate can be reduced by a factor of 10 or more. The standard gas cylinder for the micro-MFC is a "lecture-bottle" size, with a 2 liter internal volume, and the capacity for 170 well tests at 30 minutes per test. At least 1000 liters of IPA would be required to run the same tests, at a cost of $4000 (Lovelock and Stowell, 2000), versus less than $50 for the SF_6.

The new system is modular, suitcase-sized rather than skid-mounted, and capable of running on a 12-volt automotive battery. The electronic micro-metering system has a digital set-point that is maintained at +/- 0.1% through voltage regulation, viscosity compensation and pressure control, eliminating the need for the balance and computer system for weight monitoring. The gas mass flowmeter has been reduced in size and output, but still operates under the same principle and with the same degree of accuracy and precision. Figure 2 shows the simplified schematic of the new "MicroMod" tracer- injection system, and Table 11 lists the comparative specifications for the three commercial tracer-injection systems now in use.

Table 11. Comparison of specifications between commercial tracer injection systems.

System Name	Dimensions	Transport	Power	Gas Tracer Specifications	Liquid Tracer Specifications
MaxiSkid	1.8 x 3.6 m	Flatbed Truck	5000 watt 120/240 VAC	1 - 20 slpm, 40 bar 5 x 5500 l (STP) 3% propane, 1% SF_6	0.5 - 2.5 kg/min, 25 bar 750 l Tank 30% NaBr, Benzoate
MiniSkid	1.2 x 3.2 m	Small Pickup or Trailer	3500 watt 120/240 VAC	0.5 - 3 slpm, 40 bar 1 x 4000 l (STP) 1% - 2% SF_6	0.1 - 0.75 kg/min, 100 bar 200 l Tank 30% Benzoate
MicroMod	0.25 x 0.5 m	Suitcase	300 watt 12 VDC	0.01 - 0.1 slpm, 55 bar 1 x 250 l (STP) 5% - 8% SF_6	0.01 - 0.05 kg/min, 300 bar 2 l Jug 0.5% - 2% PAS

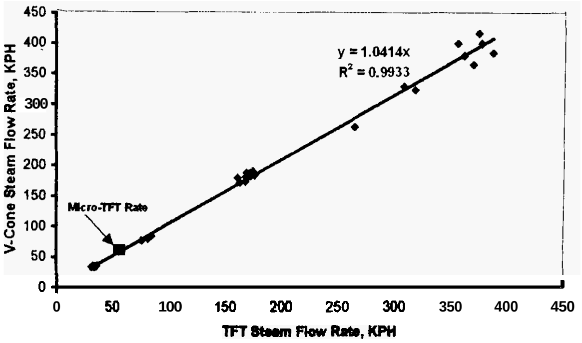


Figure 3. MiniSkid TFT-measured steam flow rate versus V-cone steam flow rate for an inter-tie pipeline at Coso. The recent MicroMod TFT-measured steam flow rate is also plotted.

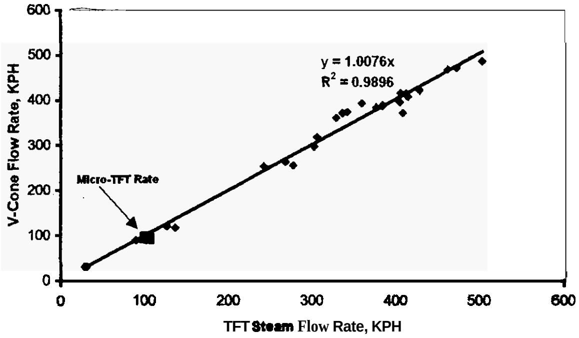


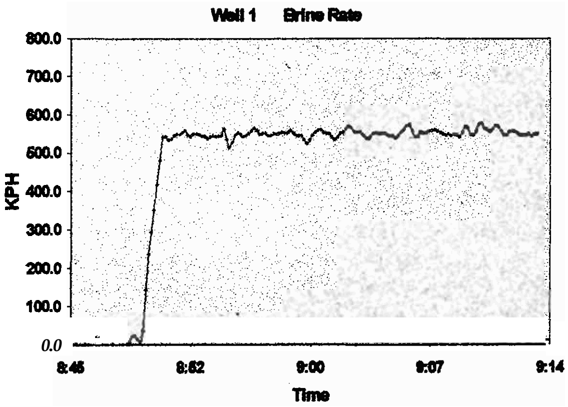
Figure 4. MiniSkid TFT-measured steam flow rate versus V-cone steam flow rate for a second inter-tie pipeline at Coso. The recent MicroMod TFT-measured steam flow rate is also plotted.

A test of the micro-MFC was conducted at Coso during routine testing of flowmeters used to measure steam flow in inter-tie piping between different lease areas of the field. Since the inter-tie flow rate is important for lease royalty payments, the V-Cone flowmeters are checked by TFT regularly to confirm proper operation and calibration. Although the latest measurements were performed during a period of low inter-tie flow at the two stations tested, the micro-MFC data falls on the trend line for previous tests using the fult-size MFC, as seen in Figures 3 and 4.

The complete MicroMod tracer-injection system was tested at a geothermal site in Hawaii, using SF_6 and PAS tracers. Limited flow metering is available in the well field and power plant, hence the need for TFT. Since the flowmeters were not inspected and calibrated prior to the test, this is not considered a validation test. However, the sum of the well steam flow by TFT agrees to within 2% of the total steam condensate flow from the plant, and the total production well flow agrees to within 5% of the total injection well flow (no cooling tower losses at this plant). The test results are given in Table 12.

Table 12. Comparison between Micro-TFT results pril 2001.

	te, kg/s		
	Steam	Brine	Total
Micro-TFT Measurements:			
ProductionWell 1	29.2	14.9	**44.1**
ProductionWell 2a	20.4	**33.1**	**53.5**
ProductionWell 2b	18.5	29.6	**48.1**
Sum of ProductionWells	68.2	77.6	**145.8**
Plant Flowmeters:			
Total Steam Condensate, Annubar	66.8		
InjectionWell Sum, Orifice			138.6



'Figure 5. Continuous TFT for brine using PAS tracer and on-line analyzer.

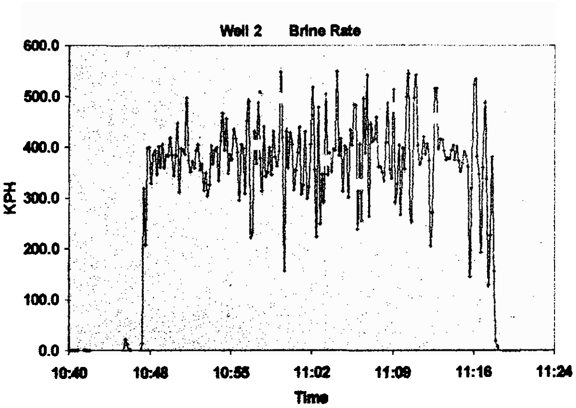


Figure 6. Continuous brine TFT for an unstable well.

6.0 ON-LINE TRACER MONITORING TECHNOLOGY

The new PAS liquid tracer can be measured directly on-site and even on-line to obtain real-time liquid mass flow rate data using a dedicated portable analyzer. Data resolution is greatly improved Over the discrete grab-sampling technique, especially under surging flow conditions. The SF_6 gas tracer can also be measured on-site using portable instrumentation so that single-phase steam and two-phase flow rate results are immediately available. Automated on-line systems are currently under development for continuous metering applications of multiple single and two-phase flow streams.

Examples of data from on-line brine flow measurements made in Nevada, USA, are shown in Figures 5 and 6, as measured by the portable field analyzer. Note that Well 1 was producing at a stable rate, while Well 2 was surging. Data from discrete samples, plotted as yellow squares, demonstrate the resolution that can be lost when not monitoring flow rates real-time.

7.0 CONCLUSIONS AND FUTURE WORK

The TFT technique for two-phase mass flow rate measurement is accurate and robust if implemented based on the original development criteria, emphasizing specific properties for the tracers and high-accuracy mass injection techniques. Evaluations of numerous tracers over 10 years indicate that sulfur hexafluoride and polyaromatic sulfonates are ideal vapor and liquid tracers. Alcohol tracers are not suitable for general TFT use. They suffer from significant liquid-phase solubility, require long mixing runs compared to the gas tracers, and exhibit losses when used on fluids with high brine fractions, resulting in erroneously high steam flow rates. The losses of alcohol may be due to chemical reactions in the liquid phase between alcohol and boron or silica. These reactions are expected to be enhanced by high brine fractions and long mixing runs.

Substantial developments have been made in the miniaturization of tracer metering equipment ("micro-TFT"), resulting in greater portability and lower cost for tracers and equipment The new polyaromatic sulfonate tracers are highly detectable, making them ideal for micro-TFT, and can be measured directly on-site and on-line using a continuous monitor. SF_6 remains the optimum vapor-phase tracer for micro-TFT due to the very high sensitivity of analysis, rapid mixing and low liquid-phase solubility.

Now that micro-quantity tracer injection equipment is available, current work is focusing on development of continuous, on-line two-phase TFT measurement. This is already feasible using a continuous instrument for PAS tracer analysis. Work is currently underway to develop a continuous analyzer for vapor-phase SF_6 tracer analysis. This technology would enable on-site two-phase flow measurement with immediate results, automated flow measurement and continuous measurement for specific applications.

ACKNOWLEDGMENTS

We wish to thank Unocal Geothermal of Indonesia and Caithness Corporation for allowing us to perform the comparison tests between alcohol and SF_6 tracers.

REFERENCES

Adams, M.C. (1995). Vapor, liquid, and two-phase tracers for geothermal systems. Proc., World Geothermal Congress, Florence, Italy, 1995.

Adams, M.C., Beall, J.J., Enedy, S.L., and Hirtz, P.N., (1991). The application of halogenated alkanes as vapor-phase tracers: a field test in the Southeast Geysers. Geothermal Resource Council Annual Meeting, 1991, Transactions vol. 15.

Adams, M.C., Yamada, Y., Yagi, M., Kondo, T., Wada, T. (2000). Stability of methanol, propanol, and SF_6 as high-temperature tracers. Proc., World Geothermal Congress, Kyushu-Tohoku, Japan, 2000.

Agamata-Lu, C.S. (2000). Chemical tracer dilution test using isopropanol, benzoate and bromide at the Broadlands-Ohaaki geothermal field. Geothermal Resource Council Annual Meeting, 2000, Transactions vol. 24.

Gallup, D.L. (1998). Method for removing contaminants from geothermal steam. United States Patent, No. 6,112,524.

Hirtz, P., Lovekin, J. (1995). Tracer dilution technique for two-phase geothermal production-comparative testing and operating experience. Proc., World Geothermal Congress, Florence, Italy, 1995.

Hirtz, P., Lovekin, J, Copp, J, Buck, C, Adams, M. (1993). Enthalpy and mass flow rate measurements for two-phase geothermal production by tracer dilution techniques. Proc., Eighteenth Workshop on Geothermal Reservoir Engineering, Stanford Geothermal Program, Stanford University, 1993.

James, R. (1970). Factors controlling borehole performance. Proceedings on the Development and Use of Geothermal Resources, Vol. 2, Geothermics Sp. iss. 2.

Lovelock, B.G. (1997). Steam flow measurement in two-phase pipelines using volatile organic liquid tracers. Proc., 19th New Zealand Geothermal Workshop, Auckland, New Zealand, 1997.

Lovelock, B.G, Stowell, A. (2000). Mass flow measurement by alcohol tracer dilution. Proc., World Geothermal Congress 2000, Kyushu-Tohoku, Japan, 2000.

Rose, P.E., Adams, M.C. (1994). The application of rhodamine wt as a geothermal tracer, Geothermal Resource Council, 1994, Transactions vol. 18.

Rose, P.E., Johnson, S.D., Kilbourn, P. (2001). Tracer testing at Dixie Valley, Nevada, using 2-napthalene sulfonate and 2,7-napthalene sulfonate. Proc., Twenty-Sixth Workshop on Geothermal Reservoir Engineering, Stanford Geothermal Program, Stanford University, 2001.

Yasuda, Y., Horikoshi, T., Jung, D.B. (2000). Development of a two-phase flow metering System. Proc., World Geothermal Congress, Kyushu-Tohoku, Japan, 2000.