CHEMICAL, TRACER APPLICATIONS AT THE BROADLANDS-OHAAKI AND WAIRAKEI GEOTHERMAL FIELDS

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Abstract

Monitoring of massflow and enthalpy of well discharges is an integral element of reservoir and production management. Several methods can be employed to determine these parameters. The chemical tracer dilution method is a recent development in the determination of mass flow and enthalpy of geothermal wells. It has been investigated as an alternative to currently employed conventional devices such as orifice plate and critical lippressure methods.

This study aims to look into massflow and enthalpy determination of two-phase lines at Br-8, Br-20 and Br-25 wells at the Broadlands-Ohaaki geothermal field. Benzoate and bromide ions were utilized as the water phase tracer, and isopropanol as the gas tracer. Results indicated that Br-8 has a waterflow of about 17 kg/s and a steamflow of about 4.8 kg/s, resulting in a total massflow of about 21.8 kg/s, and an enthalpy of about 1000 kJ/kg. Br-20, on the other hand, has a total mass flow of approximately 41.5 kg/s, wherein the water flow is about 32 kg/s and steam flow is 9.5 kg/s. It has a calculated discharge enthalpy of about 990 kJ/kg. For Br-25, the steam flow is about 16 kg/s, the water flow is 29 kg/s, and the total mass flow is 45 kg/s, with a computed enthalpy of about 1400 kJ/kg. Compared to the output tests, large variations in the mass flows were obtained, ranging from 9-240%. However, acceptable variations of 2.8-6.1% in the enthalpy values were obtained for Br-8 and 20, while a large deviation of 31% was obtained for Br-25. The massflow deviations may be due to the sensitivity of the method to errors in sampling and analysis (e.g. dosing rate measurement, loss of constituents during sampling/ analyses). The effect on the enthalpy is not very significant, except for well Br-25. Also, the output tests and tracer tests were not conducted at the same time frame, hence, accurate comparison of the tracer data with other measured data was not possible.

The application of chemical tracers in steam transmission lines was also investigated at Lines B (20" pipe) and G (48" pipe) in the Wairakei geothermal field. Isopropanol was used for the determination of steam flows, while bromide was used to monitor the scrubbing efficiency at these two lines. The steam flows obtained are 13.3 kg/s and 30.2 kg/s, for Line B and G, respectively, Compared to measured flow data, a difference of <0.1% in the steam flow was obtained for Line B, while a large difference of 58% was obtained for Line G. The difference may be due to opening of the vents during testing at Line G, which caused significant pressure drop at the pipeline. Hence, the steam flow obtained may indeed have been significantly lower at that time. The scrubbing efficiency of 0.794%/m for Line B and 0.079%/m for line G, which were previously determined by Bacon and Tracey (1984), were used in simulating the theoretical bromide concentrations obtained from the drain pot discharges. The results showed consistent trends for Line B, however, Line G is difficult to simulate due to the change in the steam line condition.

1.0 Introduction

1.1 Objective of the Study

This project investigates two applications of chemical tracers in surface geothermal pipe work, namely a two-phase line tracer test and a steam line tracer test. The two-phase line tracer, composed of isopropanol and bromide/benzoate, is used to measure steam and water flows for the calculation of discharge enthalpy. This technique is being assessed for its accuracy as an alternative method to conventional mass flow and enthalpy measurements.

The *steam* line tracer, consisting of isopropanol and bromide, on the other hand, is **used** for the measurement of steam flows in the *steam* transmission line, and the evaluation of the scrubbing effect **by** measuring the Br concentrations in **drain** pot discharges. This is of particular interest for monitoring the deposition of silica scales onto the turbine blades.

1.2 Tracer Dilution Technique

Mass flow and enthalpy measurements in two-phase geothermal wells are important reservoir and production parameters to monitor during exploitation. Trends in these parameters with time is an important reservoir management tool as **processes** occurring in the reservoir may be inferred. For instance, decreasing enthalpy trends with time may suggest cooling of the reservoir due to reinjection returns or inflow of cold water. Predicting reservoir response to exploitation through these trends at an early stage facilitates in instigating measures to prolong the life of the reservoir.

Several methods are available for the measurement of the mass flow and the enthalpy of a well. The simplest involves chemical geothermometers (Fournier and Potter, 1982, from **Hirtz,** et al. 1993). For instance, the discharge enthalpy *can* be calculated based on reservoir temperature estimates from the **quartz** geothermometer assuming that the reservoir fluid is comprised of a single-liquid phase. Underestimated values can be obtained, however, if some of the fluid enters the well bore as *steam* as an effect of boiling in the reservoir (Hirtz, et al., 1993).

Conventional and accurate methods of mass flow and enthalpy measurements in two-phase lines involves physically measuring the water and steam flows separately using the orifice plate or James lip-pressure methods. Using the orifice plate method, well fluid is passed through a cyclone separator, and *steam* and water flows are measured independently **by** calibrated orifice and manometer. **This** is the most accurate but also the most expensive method. **A** cheaper and more common technique of measuring two-phase flow is **by** the James lippressure method, where the well is discharged to a silencer **equipped** with lip-pressure gauge to measure the steam flow, whle water flow is determined from weirbox measurements (Armstead, 1983). **These** methods involve isolation of the test well from the production line. In most geothermal fields such **as** Wairakei and Broadlands-Ohaaki, when production is disrupted, the measurements become very expensive to undertake since the power station runs on base-load. In some Philippine fields, periodic monitoring using these output tests have been limited or sometimes **stopped** due to environmental constraints and the lack of spare capacity test wells due to an increase in the power load. Hence, monitoring of mass flows and enthalpy trends are often times based on limited or outdated **data** (Barroca, et al., 1994).

Alternative measures have been sought to eliminate this problem, including the use of on-line bore output measurements **by** the chemical tracer dilution technique, described extensively **by Hirtz**, et al. (1993). Several studies have already been undertaken using this method, i.e. at the Coso Geothermal field (**Hirtz**, et al, 1993), at the Wairakei and Ohaaki fields *(Carey,* B., et al., 1996) and at some Philippine fields (Jordan and Barroca, 1991; Barroca, et al., 1994; Barroca and Reyes, 1995; Salonga and Siega, 1997). The basic principle of this technique lies on the relationship between the mass flow and its dilution effect on an injected chemical tracer. Aqueous and gas tracers are injected at a constant rate in an injection point on the two-phase line. Water and gas samples are then collected at **an** appropriate sampling point downstream of the line. The following criteria must be satisfied in the selection of chemical tracers (**Hirtz**, et al., 1993, Lovelock, 1997): (a) complete partitioning of each tracer to their respective phases, i.e. there should be minimal carry-over of the aqueous tracer to the steam phase and vice versa; (b) the tracers should not degrade at the two-phase line conditions; (c) tracer solutions should be *easy* to manage and handle during injection; (d) availability of accurate analytical methods for quantitatively determining the chemical constituents of interest; (e) low background concentration of tracer constituents in the line to ensure (f) *cost* effectiveness.

Several aqueous tracers, such **as** inorganic ions (e.g., Mg^{+2}, F, Br^-, Li^+) and organic chemicals (e.g., fluorescein dye, benzoic acid) have been considered for testing. Some *gas* tracers include ethane, propane and helium. For instance, intensive tests at the Coso geothermal field and at Roosevelt Hot Springs, Geothermal field involved fluoride and propane **as** the chemical tracers (Hirtz, et al., 1993). Testing of $MgCl_2$ and N_2

tracers is being conducted in the Palinpinon field Results of these tests showed good correlation with the conventional James lip pressure method. These studies made use of compressed gases for the vapour tracer, in compliance with the criteria for selection listed above. More recent studies investigated the use of low-boiling (volatile) organic solvents as alternative gas tracers. These chemicals are injected as liquid, but at higher temperature conditions, they occur as gases. Organic solvents have the advantage over compressed gases in that (a) they are miscible with the aqueous tracer, hence the solution is easier to handle and can be injected with the same pumps used for the liquid tracer, (b) they can be injected at higher flow rates compared to gases, and (c) sampling is simplified as the gas phase tracer is sampled as a liquid by condensing the steam through a cooling coil (Lovelock, 1997).

The water flow (WF) was calculated from the aqueous tracer concentration by using the following equation:

$$\mathrm{WF\ [kg/s]} = \frac{\text{tracer injection rate [g/s]}}{\text{(tracer conc. in water - tracer conc. in background sample) [g/kg]}}$$

The steam flow (SF), on the other hand, was calculated from the gas tracer concentration using the equation below:

$$\mathrm{SF\ [kg/s]} = \frac{\text{tracer injection rate [g/s]} - (\mathrm{WF[kg/s]} * \text{tracer conc. in water [g/kg]})}{\text{tracer conc. in steam [g/kg]}}$$

From these computed mass flows, the total discharge enthalpy can be calculated by:

$$Ht = \frac{SF*hg + WF*hf}{SF + WF}$$

where hg and hf are the vapor and liquid enthalpies at the separation pressure (Contact Energy Manual; Lovelock, 1997).

1.3 Background of selected tracers and test wells

For this study, sodium benzoate and bromide were used as aqueous tracers for the determination of water flow, while isopropanol was used as a gas tracer for determination of the steam flow. These have been initially tested at some two-phase lines at the Wairakei geothermal field, however, the results were not very promising (Bacon, pers.comm.).

These tracers, specifically benzoate and isopropanol are of interest for their application in Philippine fields. Isopropanol has not been tested in the Philippines, but is being considered for testing. Tests using sodium benzoate have been conducted at the Palinpinon and Leyte Geothermal fields (Jordan, 1996; Salonga and Siega, 1997). The use of bromide as an aqueous tracer has been also been studied, but it was not a viable tracer, due to economic considerations since some fields have relatively high background bromide concentrations which requires injection of highly concentrated tracer solution. However, bromide has been included in this study as a reference, since it is the more established water tracer in the Broadlands-Ohaaki field. Besides, simultaneous analyses of the benzoate and bromide composition by ion chromatography can be conducted.

Wells Br-8, Br-20 and Br-25 were chosen for this study, after evaluation of a few other wells. These well have been selected since representative water and steam phases can be collected at the same sampling pressure, while providing a range of flow regimes and variations in sampling orientation.

Br-8 had an average measured output of 55 T/hr at a WHP of 4.4 bg, and an enthalpy of about 950 kJ/kg when it was tested on 16.6.97. Mass flow had increased since the previous output test in 7.96. Based on the water chemistry, the reservoir temperature from the quartz geothermometer, Tqtz, was determined to be about 200°C (Carey, B, et. al., 1997). The two-phase line has a high water content, and it was difficult to collect steam condensate during the tracer test. The sampling point is horizontally oriented (side-tapping). Figure 1 illustrates sampling point orientation for the three test wells.

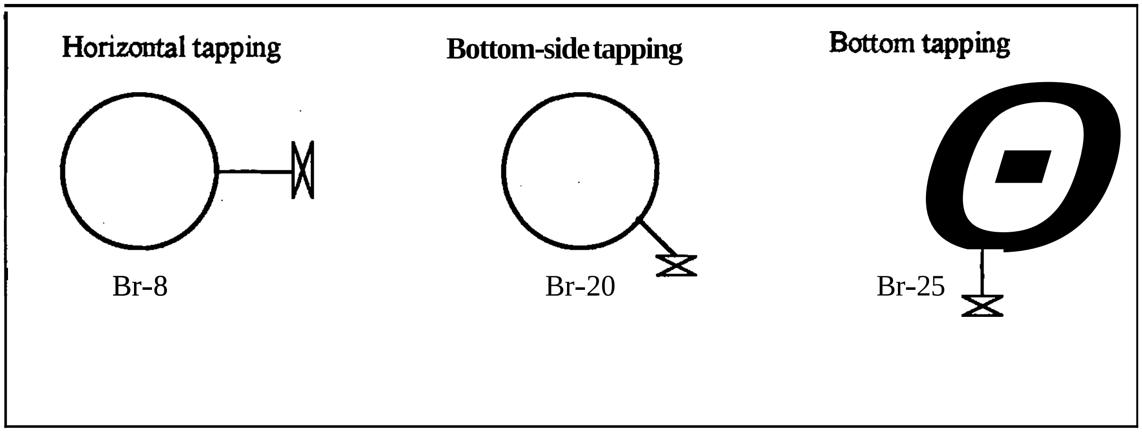


Figure 1. Sampling point Orientation in two-phase lines

During its 8.7.97 output test, Br-20 had an average measured mass flow of 117 T/hr at 10 bg WHP and an enthalpy of approximately 1030 kJ/kg. The mass flow has decreased since its last output test in 2.96. From quartz geothermometry, Tqtz of the well is about 255°C (Carey, B, et al., 1997). This well has a slug flow, and the sampling point is oriented on the bottom side of the line.

Br-25 was discharged on 3.7.97, and the mean output measurement was 108 T/hr at 10 bg WHP, with an enthalpy of about 1050 kJ/kg. Compared to its 12.96 output results, the mass flow had decreased. From the discharge chemistry, this well has quartz temperature of 250°C (Carey, B, et. al., 1997). The sampling point is oriented vertically at the bottom of the two-phase line.

1.4 Steam Line Tracer Test

Application of chemical tracers in the steam line was also studied. The steam line tracer consists of isopropanol and bromide. Isopropanol was used for the steam flow determination, while bromide was monitored in the drain pot discharges to assess the scrubbing effect in the steam pipeline. This test is used to estimate the silica and chloride concentration in the steam phase, as these constituents cause deposition in the turbine blades. The proportion of the constituent transferred from the steam phase into the condensate phase is the scrubbing efficiency. Results of a previous study (Bacon and Stacey, 1983) showed that the scrubbing efficiency of a saturated steam line depends on both the drain pot efficiency and transport mechanics of water droplets within the steam phase. Larger pipe diameter, higher steam velocities and improved insulation tend to promote the travel of water droplets down the line.

This test was conducted on two steam transmission lines with different pipe diameters, namely, Line B and line G. Line B is a 20" (508 mm.) diameter intermediate pressure (IP) steam line, with measured mass flow of about 13.3 kg/s. The pipe is insulated with asbestos and malthoid cladding. Line G is a 48 (1220 mm) low pressure (LP) steam line, with measured mass flow of about 72.2 kg/s. It is insulated with fiberglass and aluminium cladding (Bacon, pers. comm).

2.0 Methodology

2.1 Two-phase Line Tracer Test Methodology

Field tracer test preparations

The set-up shown in Figures 2 and 3 illustrate the schematic diagram for the tracer injection and sampling procedures. The set-up and methodology currently used by Contact Energy was adapted for the tracer tests in this study.

Materials required for the tracer test include (a) 50-ml water sample bottles with labelling tape, (b) 10-ml tubes (with labelling tape) with screw caps containing about 0.3 g NaF for isopropanol sampling in steam condensate, (c) zinc acetate solution for sample pre-treatment, (d) sampling forms, (e) spare tools and connectors, (f) cables, (g) injection set-up, and (h) a timer.

Preparation of Tracer Sample

For the two-phase tracer test, the tracer solution consists of 53,910 ppm benzoate and 81,060 ppm Br in 50% (v/v) of isopropanol. The steam line tracer, on the other hand, consists of 150,510 ppm of Br in 50% (v/v) isopropanol, The detailed procedure for the preparation of the injected tracers is shown in Appencllx 1.

Injection Set-up

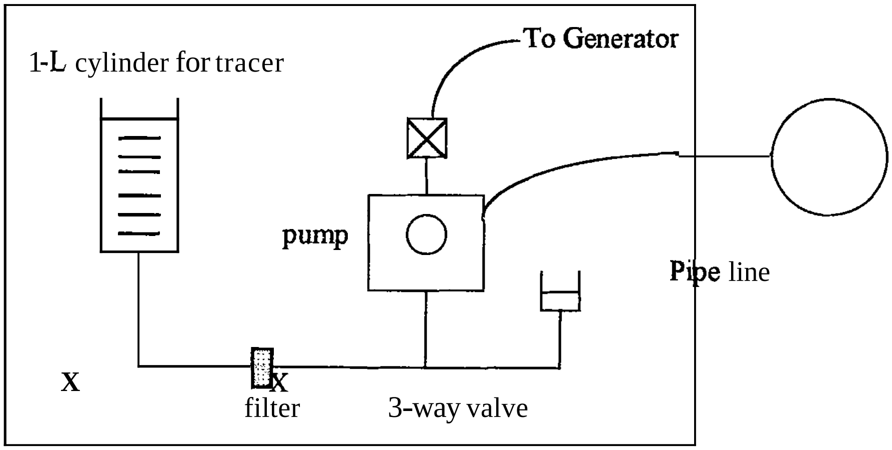


Figure 2. Tracer Injection Set-up.

Before the set-up was connected, the sampling valve on the pipeline was opened and discharged to ensure it is clear of any blockage. The set-up was then connected to the generator. The hose injection was connected to the pipeline valve, and the valve opened. The tracer reservoir was then filled above the 1000-ml graduation. and three-way valve set to tracer side. The pump was set to 100% (for the two-phase tracer test) or 40% (for the steam line tracer test).

The wellhead pressure was checked and all necessary information (i.e., Well ID. WHP. sampling pressure, dosing rate) was recorded on the sampling sheet. Injection was initiated when the sampler had signaled that background sampling had commenced. The dose rate was obtained by measuring the time it takes to inject

800 ml of tracer, i.e. from 1000-ml mark to **200-ml** mark on the cylinder. The injection was stopped when the sampler had signaled that tracer samples had **been** obtained.

After injection, the pressure reducing valve was checked to see that no fluid had discharged from it. The pump was then switched off, and the **bypass** valve opened. The sample point valve was then closed, and the injection hose disconnected. The pipeline valve was opened to flush out the residual tracer.

Sampling Set-up

The sampling equipment, consisting of a Webre separator, pressure gauge, cooling coils, and a supply of cold water. was setup at the sampling point about 50-100 m downstream of the injection point (Figure 3). The pipeline was opened and checked if dry steam and water samples could be collected at the same sampling pressure. The Webre separator was then connected to the sampling port. The cooling coil for the separated water was placed in the cold water bucket for collection of background samples. The sampler then signaled to the person at the injection point that background sampling had finished and that tracer injection may start.

When tracer injection was initiated, the tracer was allowed to equilibrate for about 2 min/ 100m length of pipe, based on previous tests using fluorescein dyes. While waiting, water and steam was run through the coils, but not placed in the cold water bucket to conserve cold water. When equilibration was achieved, steam condensate and separated water samples, for bromide and benzoate analyses, were collected in 100ml plastic bottles while steam condensate and water samples for isopropanol analysis were collected in screw-capped glass tubes containing NaF powder, which prevented the degradation of the alcohol in the sample. The alcohol samples were kept cold to prevent rapid volatilization which will incur lower measured alcohol concentrations. Zinc acetate was added to the samples to precipitate H_2S, as the HS^- and S^{-2} ions may interfere in the IC analysis.

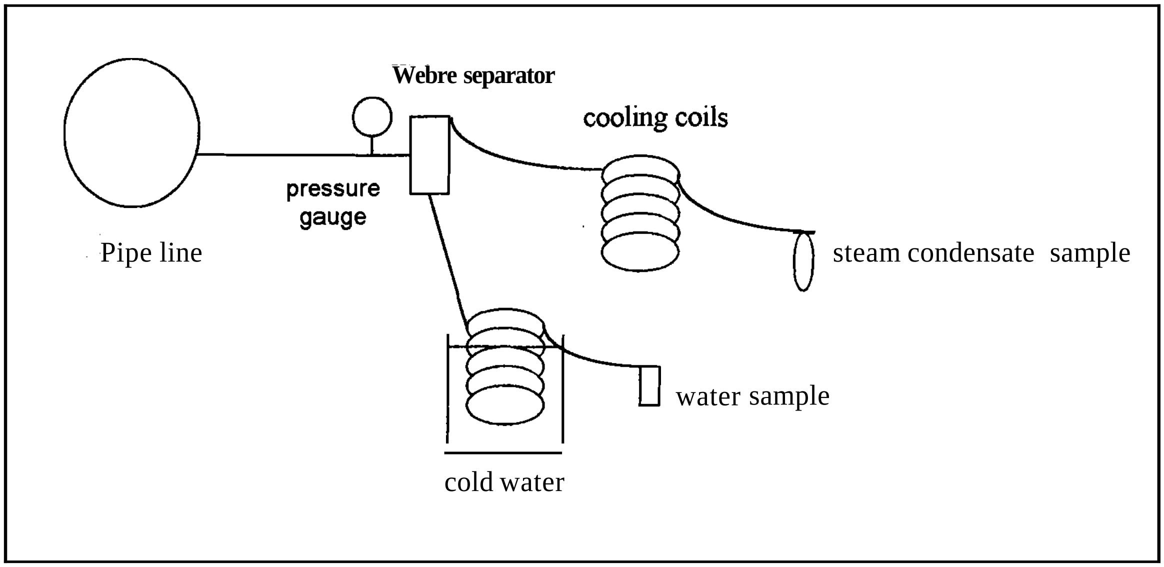
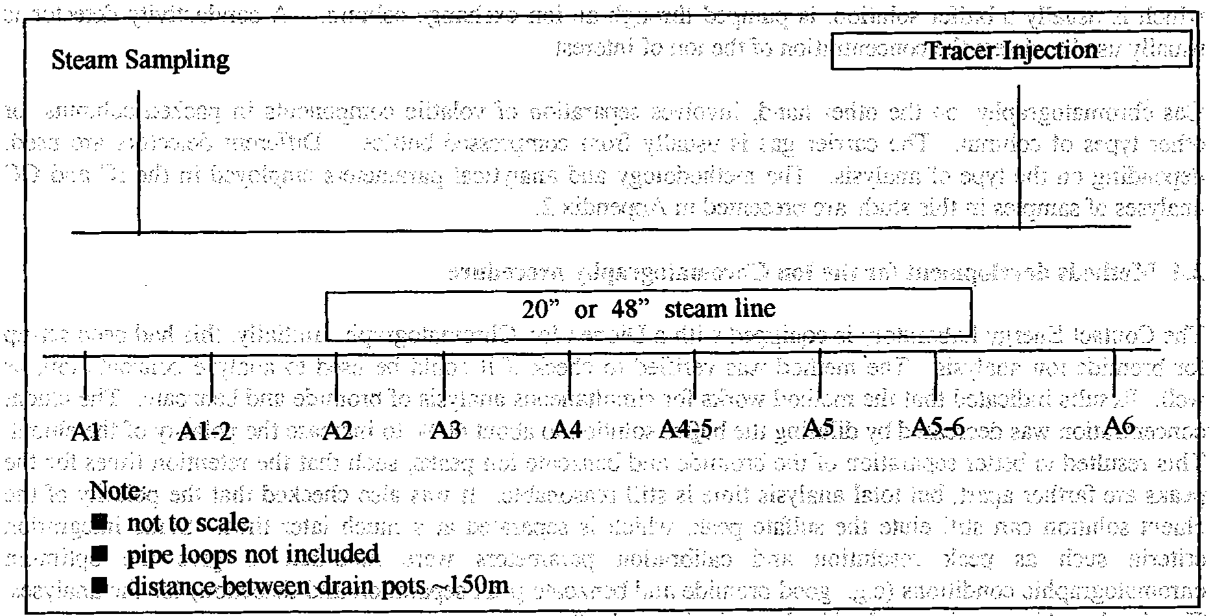


Figure 3. Tracer Sampling set-up.

2.2 Steam line Tracer Test Methodology

The injection and sampling set-up for the steamline tracer test is shown in Figure 4 . Bromide and isopropanol tracer solution was injected at the point where separated brine is injected to prevent corrosion of pipelines. This is between drain pots **A6** and **A5-6**. The steam sampling point was setup on the line just upstream of where ***steam*** goes into the power station. The steam condensate sample was collected for isopropanol analysis in the steam phase by using a cooling coil. Condensate samples for bromide analyses were also collected at all the drain pots between the injection and the sampling points.



Note:
- ■ not to scale
- ■ pipe loops not included
- ■ distance between drain pots ~150m

Figure 4. Steam line tracer set-up.

2.3 Theory of Chromatography

Chromatographic methods of analysis of the tracer constituents were employed in this study. The benzoate and bromide composition were determined by ion chromatography (IC) while the isopropanol concentration was analyzed by gas chromatography (GC). Chromatography involves two phases, stationary and mobile phases. The stationary phase is usually a separative column, where separation of constituents occur, and the mobile phase is usually gas (GC) or liquid (LC). Separation is based on the affinity of a constituent to the stationary phase. The detector identifies a constituent by its retention time, which is based on standardization runs. A typical schematic

1974). Variations in the set-up are in the type of column, eluent and detector. The column, detector and injector, are usually placed in an oven to regulate temperature conditions.

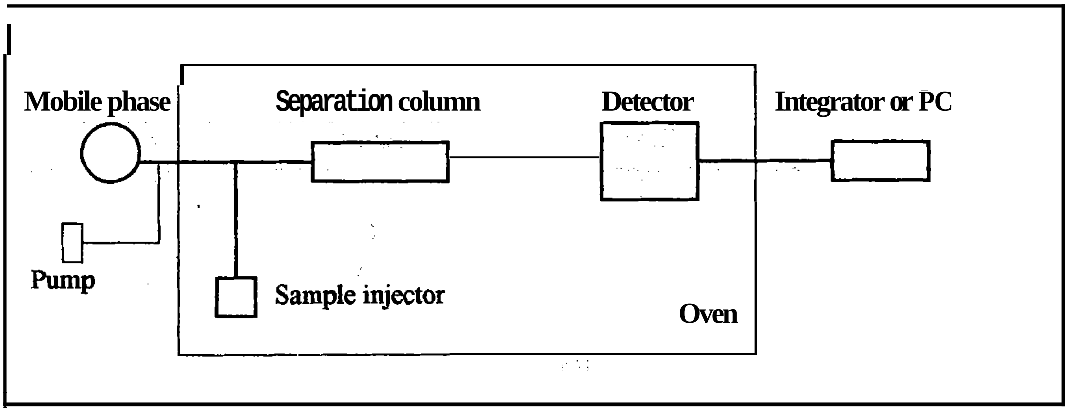


Figure 5. Schematic Diagram of a Basic Column Chromatography instrument

Ion chromatography, a "subset" of high-pressure liquid chromatography (HPLC), involves the separation of ionic species in a chromatographic column at pressurized conditions. The liquid mobile phase or eluent, which is usually a buffer solution, is pumped through an ion exchange column. A conductivity detector is usually used to detect the concentration of the ion of interest.

Gas chromatography, on the other hand, involves separation of volatile components in packed columns, or other types of column. The carrier gas is usually from compressed bottles. Different detectors are used, depending on the type of analysis. The methodology and analytical parameters employed in the IC and GC analyses of samples in this study are presented in Appendix 2.

2.4 Methods development for the Ion Chromatography procedure

The Contact Energy Laboratory is equipped with a Dionex Ion Chromatograph. Initially, this had been set-up for bromide ion analysis. The method was verified to check if it could be used to analyze benzoate ion, as well. Results indicated that the method works for simultaneous analysis of bromide and benzoate. The eluent concentration was decreased by diluting the buffer solution to about 60%, to increase the polarity of the eluent. This resulted to better separation of the bromide and benzoate ion peaks, such that the retention times for the peaks are farther apart, but total analysis time is still reasonable. It was also checked that the polarity of the eluent solution can still elute the sulfate peak, which is separated at a much later time. Some integration criteria such as peak resolution and calibration parameters were modified to give the optimum chromatographic conditions (e.g., good bromide and benzoate peak separation and detection) for the analyses. The developed integration method is shown in Appendix 3.

2.5 Analysis of Samples

Bromide concentrations were determined for the background water samples, and benzoate and bromide in the tracer water samples were analyzed by ion chromatography. These were conducted at the Contact Energy Laboratory in Wairakei. The steam condensate and water samples for isopropanol analysis by gas chromatograph were sent to the Institute of Environment and Science Research blood-alcohol laboratory in Wellington. Detailed methodology for these analyses are given in Appendix 2. Standard and sample chromatograms are shown in Appendix 4.

3.0 Results and Discussion

3.1 Mass flow and enthalpy calculation using chemical tracers in two-phase line

The sampling data obtained for the two-phase tracer test are summarized in Table 1

Table 1. Sampling Data for two-phase tracer test

Tracer : Benzoate + bromide + isopropanol
Date tested : 01/09/97

Well	Br-8	Br-20	Br-25
WHP (bg)	3.2	11.5	11.0
Micrometer Setting (%)	100	100	100
Dosing Rate (mls/s)	4.10	4.00	4.06
Sampling Pressure (bg)	1.3	0.9	5.9
Sampling Point Orientation	Side-tapping(hor.)	bottom-side	bottom (vert.)
Remarks	high water	slug flow	good sampling

The water flow (WF) was calculated from the benzoate and bromide concentration by using the following equation :

$$\text{WF [kg/s]} = \frac{\text{tracer injection rate [g/s]}}{\text{(tracer conc. in water - tracer conc. in background sample) [g/kg]}} \qquad \textit{(Eqn. 1)}$$

The steam flow (SF), on the other hand, was calculated from the isopropanol (ROH) concentration using the equation below:

$$\text{SF[kg/s]} = \frac{\text{tracer injection rate [g/s]}-(\text{WF[kg/s]* ROH in water [gkg]})}{\text{ROH in steam [g/kg]}} \qquad \textit{(Eqn. 2)}$$

From these computed mass flows, the total discharge enthalpy can be calculated by:

$$Ht = \frac{SF*hg + WF*hf}{SF + WF} \qquad \textit{(Eqn. 3}$$

were hg and hf are the vapour and liquid enthalpies at the separation pressure.

For the tracer dilution method, accurate measurement of all the sampling and analytical parameters is essential. For instance, care must be taken in sampling, especially, for the isopropanol, as this is a very volatile constituent. It is important that the steam condensate or water sample collected is cold, to ensure that no isopropanol vaporises, which will incur losses in concentration and higher calculated steam flows. This is also the case for the aqueous tracer. Hence, sampling and analytical care are required to ensure accurate high quality concentration data. Aside from these, measurement of the dosing pump rate must also be accurate, as the tracer flow rate is an important variable in the calculation of the mass flows. The enthalpy values are not significantly affected since it is not very sensitive to these errors.

The injected tracer consisted of 53,520 ppm of benzoate, 80,945 ppm of bromide and 396,000 ppm of isopropanol. The isopropanol concentration was based on previous analyses, as it was mistakenly not analysed with the batch samples. The tracer solution was injected at a rate of about 0.252 kg/hr. The benzoate to bromide ratio was about 0.66.

Calculated water flows for Br-8, Br-20 and Br-25, using the benzoate and bromide tracers are shown in Table 2 and indicate very good agreement. The values for the total mass flows and enthalpies were within 5%, whch is acceptable. Relatively higher water flows and lower steam flows are obtained from the benzoate and isopropanol tracer pair compared to the bromide and isopropanol pair. Enthalpy values are also lower for the benzoate and isopropanol pair. This behavior may be explained by the observed benzoate to bromide ratio. The ratio for the injected tracer is 0.66, but it decreased to 0.62-0.63 in the analyzed sample, giving a loss of about 5.3% benzoate. The decrease in the recovery may be due to slight degradation of the benzoate in the two-phase line. However, this small change does not significantly affect the results and the calculated mass flows from both tracers show good precision. However, no duplicate samples were obtained to give a better estimate of the precision. The limit of accuracy estimated for the water flow determination using the bromide tracer was about ± 2.5%, while for the benzoate tracer is about ± 2.7%. For the isopropanol gas tracer, a limit of accuracy for the steam flow was estimated to be about ± 5%. The factors taken into consideration include errors which may have been incurred during tracer injection (i.e., dosing rate measurement), sampling (i.e., loss of isopropanol, accuracy of Webre separator), and analysis (i.e., standard preparation, dilution, instrumentation). This corresponds to a limit of accuracy of about ± 10% for the enthalpy determination.

Table 2. Results of Mass flow and enthalpy determination from tracer test

Well No.		Br-8	Br-20	Br-25
Benzoate Concentration (mg/kg)		12.45	6.40	7.08
Br in Background sample (mg/kg)		2.10	3.95	2.72
Br in Tracer sample (mg/kg)		21.90	14.28	14.21
Net Br concentration (mg/kg)		19.81	10.34	11.50
Benz/Br		0.63	0.62	0.62
Isopropanol Conc.(%)				
Water sample		13.4	2.11	7.35
Steam Condensate sample		292	163	88.8
Cv/Cl		21.8	77.25	12.08
Isopropanol	Water flow (kg/s)	17.8	34.7	31.4
+	steam flow(kg/s)	4.81	9.66	15.91
Benzoate	Total MF (kg/s)	*22.7*	*44.4*	*47.5*
	Calc. H (kJ/kg)	*989*	*976*	*1349*
Isopropanol	Calc. WF (kg/s)	17.0	32.5	29.2
+	Calc. SF (kg/s)	4.85	9.68	16.08
Bromide	Total MF (kg/s)	*21.8*	*42.2*	*45.3*
	Calc. H (kJ/kg)	*1008*	*1001*	*1383*
% Difference rel. to (Isop.+ Br)				
Total MF		-4.03	-5.26	-4.73
Calc. H		1.87	2.5	2.5

It is also interesting to note the distribution of the isopropanol in the water and steam phase. This parameter, Cv/Cl, is affected by the temperature and pressure in the two-phase line (Lovelock, pers. com.), and is also related to the vapor pressure of isopropanol (Brown, pers. comm.). In geothermal environments, this ratio should be within 10-25 (Contact Energy Manual). The ratios for wells Br-8 and 25 are within this range, however, the value for Br-20 is anomalously high. This may be due to loss of isopropanol during sample collection of the water phase. A more expected isopropanol concentration in the water phase, assuming a Cv/Cl ratio of 12, is about 13.5 ppm. This would give a steam flow of about 7.3 kg/s, which is almost 25% lower than the calculated value of 9.68 kg/s. Consequently, isopropanol loss will affect the calculated total mass flow and enthalpy values.

The Contact Energy Lab has established a spreadsheet for tracer calculations, which has macro programs utilizing Eqns. 1-3 above. The steam table program by Dr. Freeston (steamtab.xls) file has been linked with the calculation program to automatically compute the enthalpy values. Sample outputs are shown in Appendix 5. Comparison of the tracer results using this spreadsheet with the calculated results show the deviation to be within <3.5% difference for the water flow, within <5.5% difference for the steam flow, <4% for the total mass flow and < 3% for the enthalpy values. The slight difference is due to the approximation of the enthalpy values, since the spreadsheet uses the linked steamtab.xls program, while the tracer calculations were based on the Rogers and Mayhew steam tables.

From the above computations, Br-8 has a water flow of about 17.0 ± 0.5 kg/s, a steam flow of about 4.8 ± 0.2 kg/s, resulting in a total mass flow of about 21.8 ± 0.7 kg/s, and enthalpy of about 1000 ± 100 kJ/kg.

Br-20, on the other hand, has a total mass flow of approximately 42.0 ± 1.3 kg/s, wherein the water flow is about 32.5 ± 0.8 kg/s and steam flow is 9.5 ± 0.5 kg/s. It has a calculated discharge enthalpy of about 990 ± 99 kJ/kg.

For Br-25, steam flow is about 16.1 ± 0.4 kg/s, water flow is 29.2 ± 0.7 kg/s, and total mass flow is 45.3 ± 1.1 kg/s, with a computed enthalpy of about 1383 ± 138 kJ/kg.

3.2 Comparison to Tqtz and Output Test Results

The discharge enthalpy based on the quartz temperature and the aqueous silica concentrations were calculated for the three test wells. The results show that Br-8, Br-20 and Br-25 have discharge enthalpies of 852 kJ/kg, 1115 kJ/kg, and 1085 kJ/kg, respectively, as shown in Table 4. An acceptable difference of 7.6%, was obtained for Br-20, while higher differences of 17.4% and 27.5% were obtained for Br-8 and Br-25, respectively.

Table 3. Comparison of Discharge Enthalpy based on Tqtz and tracer results

Well	Br-8	Br-20	Br-25
Tqtz H (kJ/kg)	852	1115	1085
Tracer H (kJ/kg)	1000	1030	1383
% difference	-17.4	7.60	-27.5

Tracer results were also compared to output tests results. Ideally, to compare the tracer dilution technique with conventional output measurements, these tests must be conducted at the same reservoir and well conditions, i.e. within the same time frame. Well conditions vary over months at Broadlands-Ohaaki, hence, different well characteristics are expected at different times, even using the same method of measurements. The previous output measurememts were conducted in July 1997, three months before the tracer tests. Water and steam flows were calculated from the discharge enthalpy at the sampling WHP. The results are summarized in Table 4, and include mass flow results from the 1996 output measurements.

Comparing the 1996 against the 1997 output results indicate that Br-8 seems to have a relatively stable mass flow, ranging from 18-25 kg/s. The mass flow of Br-20 has had a very large decrease from 56.6 kg/s in Feb-96 to 12.9 kg/s in Sep-97. Br-25 also had a relatively large decrease in the mass flow, which is from 40.5 kg/s in Dec-96 to 23.8 kg/s in Jul-97. Discharge enthalpies are shown to be quite stable for the three wells, with only a slight decrease of about 30-50 kJ/kg from 1996 to 1997.

The differences in the discharge enthalpies between the tracer test and the last output tests results for Br-8 and Br-20 are quite acceptable, 2.82% and 6.11%, respectively. However, Br-25 has about 30% difference from the output test.

Table 4. Tracer vs. Output test results

Well No.	Steam Flow (kg/s)	Water Flow (kg/s)	Total Flow (kg/s)	Enthalpy (kJ/kg)
Br-8: Nov-96 output			18.3	1034
Jun-97 output	4.6	20.40	25.0	1000
tracer results	4.9	17.00	21.8	1008
% Difference*	-5.43	16.67	12.73	-0.80
Br-20: Feb-96 output			56.6	1097
Jul-97 output	1.5	11.45	12.9	1030
tracer results	9.7	32.50	42.2	1001
% Difference*	-568	-184	-227	2.82
Br-25: Dec-96 output			40.5	1195
Jul-97 output	3.0	20.8	23.8	1050
tracer results	16.1	29.20	45.3	1383
% Difference*	-437	-40.4	-90.3	-31.7

*%Difference between 1997 output and tracer results

Comparing the tracer results to the latest output test results indicate that only the Br-8 tracer result has mass flow and enthalpy values comparable to the output test results. Large % differences, of -568% and -437% were obtained for the steam flows of Br-20 and Br-25, respectively. The water flow measured for Br-20 also has a very large deviation of -184%. The large deviation in the steam flow measurements can be attributed to several factors, one of which is the error incurred due to loss of isopropanol during sampling. Volatilization of isopropanol results in a lower recovery, which will incur higher steam flow determinations. Incorrect measurement of the dosing rate can also contribute to this deviation, as the tracer mass flow is an integral variable in the calculations. Another factor which may have affected the mass flow calculation is the orientation of the sampling port. This has not been taken into consideration in this *study,* but a previous study showed that sampling point orientation should be considered in tracer tests, as it can determine whether representative sampling has been conducted or not (Barroca, G.B., and Reyes, R. L., 1995). For instance, Br-8 has a horizontally oriented sampling point, which could yield representative steam and water phases. Br-20 and Br-25, on the other hand, have sampling points oriented from the bottom part of the two-phase line, hence, representative steam samples may not have been collected The efficiency of the Webre separator can also contribute errors in the mass flow calculations, since carry-over of water to the steam phase can dilute the isopropanol in the steam phase, resulting in higher measured steam flows. An important consideration for tracer tests is the assumption that uniform mixing of the chemical tracer in the two-phase line occurs, and that the two phases have a uniform or laminar flow. In the occurrence of slug flow, however, this assumption does not hold, which may explain the very large deviation of the Br-20 results. The distance between the injection and sampling points should be considered, as well, since this determines the degree of mixing of the tracer solution in the two-phase line. For the tracer tests conducted, a distance of ~100m between injection and sampling point was employed. This may not have been sufficient enough to ensure complete mixing of the tracer in the two-phase line

3.3 Accuracy of Tracer Test vs. Other methods

The limits of accuracy for output test measurement using well head separation (orifice and weir) is about ±25 kJ/kg on the enthalpy, while for the James lip-pressure method is about ±50 kJ/kg (Clotworthy, pers. comm.).

Results of the two-phase mass flow measurements for this *study* are incomplete because we could not measure enthalpies using more conventional methods. Different conditions prevailed during testing, and due to time constraints, some factors, such as measuring actual mass flow and testing **at** different wellhead pressures, were not taken into consideration. The limit of accuracy for the tracer dilution method, however, was estimated to within ± 10% for the enthalpy.

3.4 Steam Line Tracer results

The sampling data obtained during the steam line tracer test at Lines B and G are summarized in Table 5.

Steam Line/Pipe Diameter	B/ 20"	G/ 48"
Micrometer setting (%)	40	40
Dosing rate (mls/s)	1.60	1.64
Sampling time (min.)	7	20
Remarks		pressure drop
Efficiency of DP (%)	40	85

The steam flow at lines B and G were also calculated using Eqn. 2. However, the term on isopropanol in water was neglected, as isopropanol will not fractionate within the steam line. The results of the steam flow calculations are shown in Table 6 :

Line/ Pipe dia.	B/ 20" SL	G/ 48" SL*
ppm isoprop	48.2	21.2
Steam Flow (kg/s)	13.3	30.2
Measured SF (kg/s)	13.3	72.2
% Difference	-0.059	58.11

*Pressure drop experienced during testing

The steam flow from the tracer method for line B is **13.3 kg/s**, which corresponds to the measured steam flow in this line. For line **G,** however, the vents opened during testing. Consequently, a decrease in line pressure and mass flow is expected. The steam flow of **30.2 kg/s** obtained may be the actual flow at that time. However, these results are not very conclusive, as it is based on only one accurate test.

Results for the bromide in the drainpot discharges are summarized in Table ***7.***

Table 7. Bromide concentration in drainaot discharges

Line/Pipe dia.	B/20"	G*/48"
Steam Sample	ND	ND
A 1	-	ND
A 112	**IND**	**ND**
A 2	**ND**	**10.09**
A 213	**IND**	-
A 3	**ND**	**(1.56**
A 4	**ND**	**18.44**
A415	**117.91**	146
A 5	**(84.6**	**1406**
A 516	*14200*	*3565*
A 6	**13.16**	**15.44**

*Pressure drop experienced during testing

The Qscharge from the first drain pot after the injection point **(A** 5/6) contains the highest bromide concentration. Most of the injected salt seem to be efficiently scrubbed out by the time the steam reaches the **A4** drain pot, approximately **500-600** m away. The steam samples were also analyzed for bromide content (carry-over), however, no Br was detected, which showed that the steam at the sampling point had been scrubbed of the Br. The drain pot at **A6** upstream of the injection point was sampled, and unexpectedly, it contained **3-6** ppm Br, which should not be the case. This can only be explained by contamination of the sample collected, as it was collected after the drainpot **A516** which had a very high Br concentration, and the sampling bucket used was not rinsed well.

Table **8** summarizes the data used for the simulation of expected bromide concentrations at the drain pots. The scrubbing efficiencies obtained **by** Bacon and Stacey **(1984)** were used to for the model.

Line	B	G
Condensation rate (kg/mhr)	**0.6107**	**0.7062**
Initial Cond. Flow **(kg/hr)**	55	**10**
Scrubbing efficiency (%/m)	**0.794**	**0.079**

Based on the model, the trends observed on the scrubbing of bromide from the steam line follows the trends using silica levels in the steam condensate obtained **by** Bacon and Stacey **(1984).** Simulation of the scrubbing in Line G was constrained by the varied conditions (i.e., pressure drop) experienced during testing. The scrubbing efficiency of **0.794%/m** for Line B and **0.079%/m** for line **G,** were used in simulating the theoretical bromide concentrations obtained from the drain pot discharges. The results showed consistent trends for Line B, however, Line G is difficult to simulate due to the change in the steam line conditions.

4.0 Conclusions and Recommendations

Based on the results of the two-phase tracer tests using benzoate and bromide as aqueous tracer and isopropanol as gas tracer, comparable results, within <5% difference, were obtained for both chemicals. The limit of accuracy estimated for the water flow determination using the bromide tracer was about ± 2.5%, while for the benzoate tracer is about ± 2.7%. For the isopropanol gas tracer, a limit of accuracy for the steam flow was estimated to be about ± 5%. The factors taken into consideration include errors that may have been incurred during tracer injection (i.e., dosing rate measurement), sampling (i.e., loss of isopropanol, accuracy of Webre separator), and analysis (i.e., standard preparation, dilution, instrumentation). This corresponds to a limit of accuracy of about ± 10% for the enthalpy determination. Further tests have to be conducted to verify the accuracy of the tracer method compared to conventional methods. Large % differences in the mass flows were obtained when results were compared to previous output tests, since these were not conducted simultaneously.

The tracer dilution method using bromide, benzoate and isopropanol tracers depend largely on the accuracy of determining the tracer concentrations. Slight errors incurred during sampling and analyses could result in a large deviation in the mass flow, which is one of the limitations of this method.

Tests should be conducted at some Philippine fields to check the applicability of the benzoate and isopropanol tracers at two-phase lines, in comparison to currently tested tracers, such as $MgCl_2$ and N_2.

The steam line tracer showed that the steam flow of 13.3kg/s measured in Line B using isopropanol gas tracer has a very high accuracy. The steam flow of 30.2 kg/s measured at Line G is much lower than the expected value of 72.2 kg/s due to the decrease in line pressure, caused by opening of the vents, during the tracer test. Further tests have to be conducted to verify these results.

Scrubbing of the steam line is very efficient, as most of the injected bromide is completely scrubbed when the steam reaches the 3rd of 4th drainpot after injection point. The steam samples collected do not contain detectable amounts of bromide, and show that it has been efficiently scrubbed. The scrubbing efficiency of 0.794%/m for Line B and 0.079%/m for line G, were used in simulating the theoretical bromide concentrations obtained from the drain pot discharges. The results showed consistent trends for Line B, however, Line G is difficult to simulate due to the change in the steam line condition.

5.0 References

Armstead, H.C.H. (1983). Geothermal Energy Second Ed. E. & F. N. Spon. N.Y.

Bacon, L. G. and Stacey, R. E. (1984). "The transport of water droplets down saturated geothermal steam lines and the development of the corrosion inhibition system at Wairakei." Proc. Conference 24, Corrosion Technology - 1984 and Beyond. Australasian Corrosion Assoc., NZ Branch.

Barroca, G.B, Reyes, R.L., and Seastres, J.S. (1994). "On-line bore output measurements using chemical tracers at Palinpinon Geothermal field" Proc. 15th PNOC-EDC Geothermal Conference 1994.

Barroca, G.B. and Reyes, R.L. (1995). "Evaluation of On-line bore output measurements using chemical tracers at Palinpinon Geotehrmal Field." Unpub. PNOC-EDC Internal Report.

Carey, B., Bacon. L., Roberts, K. and Lee, S. (1997). "Ohaalu Production Well Output Testing, June-July, 1997." Unpub. Contact Energy Internal Report.

Fritz, J.S and Schenk, G.H. (1974). Quantitative Analytical Chemistry 3rd edition. Allyn and Bacon, Inc., Boston, USA.

Henley. R.W., Truesdell, A.H., Barton, P.B. Jr., and Whitney, J.A. Fluid-Mineral Equilibria in Hydrothermal System. Reviews in Economic Geology Vol. 1.

Hirtz, P., Lovekin, J., Copp, J., Buck, C. and Adams, M. (1993). "Enthalpy and Mass flow measurements for two-phase geothermal production by tracer ddution techniques." Proc. 18th Workshop on Geothermal Reservoir Engineering. Stanford University, Stanford, California.

Jordan, O.T. and Barroca, G.B. (1991). "Use of a chemical tracer for on-line measurements of then total wastewater flows, Southern Negros Geothermal Project." Unpub. PNOC-EDC Internal Report.

Lovelock, B.G. (1997). "Steam flow measurement in two-phase pipelines using volatile organic liquid tracers."

Ohaalu Geothermal Field, 1996 Annual Report, Monitoring and Reservoir Performance. Internal Report Contact Energy Geothermal.

Salonga, N.D. and Siega, F.L (1997). "Preliminary comparison of the results of waterflow measurements using MgCl2 and Na-benzoate tracers." Unpub. PNOC-EDC Internal Report.

Thain. I.A., Stacey, R.E., and Nicholson, D.J.(1981) "Zero solids condensate corrosion in steam pipes at Wairakei." Geothermal Resource Council- Transactions, Vol. 5, Oct. 1981.