ACCURACY AND RELIABILITY ANALYSIS OF TRACER FLOW TESTING IN GEOTHERMAL SYSTEMS

Zhilin James Dong[1], Ruben Yague Jaen[1], Connor McBride[1] Stanislav Krakhin[1]

[1]MB Century, 144 Karetoto Road, Wairakei, Taupo, New Zealand

jdong@mbcentury.com

Keywords: *Geothermal, Tracer Flow Testing, Isopropanol, Benzoate.*

ABSTRACT

As a critical resource management tool, tracer dilution techniques have been used to measure steam and brine flow and total enthalpy in geothermal industries for many years. Standard operations have become part of a routine monitoring program in many geothermal fields throughout the world. Different types of tracer for gaseous and aqueous phases have been developed and used in many different geothermal fields. Tracer injection equipment, sample collection systems and tracer analyzing methods have also been developed and gradually improved over past decades. The accuracy and reliability of testing results vary depending on types of tracer, injection and collection techniques, tracer analysis methods, and testing operation procedures. This paper summarizes our many years' experience on utilizing sodium benzoate and isopropyl alcohol as tracers for flow testing in geothermal systems in New Zealand and overseas and analyses the accuracy and reliability of the available testing results.

Single gaseous and aqueous tracers have also been used to measure steam or water flow rates in single phase pipelines to verify permanent flow meters at geothermal plants. An innovative tracer testing procedure to evaluate the performance of steam purifiers has also been developed with consistent results achieved. Particular emphasis will be placed on quality control system to ensure more accurate and reliable results are achieved.

1. INTRODUCTION

As an important resource management tool, tracer dilution for measuring steam and brine flow, as well as total output enthalpy has been widely recognized and put into practical application throughout the world in numerous geothermal fields. In New Zealand, this technique has been tested and used in nearly all the geothermal fields under exploitation in the past decade. Steam tracers such as Sulfur hexafluoride (SF_6) and Isopropanol and water tracer such as sodium benzoate have been tested and used. Various testing equipment, methods and procedures have been developed and improved.

A persistent concern about tracer dilution testing over the past decade is the accuracy and reliability of these tracer tests. A great deal of effort has been made to improve the accuracy and reliability in New Zealand. This accumulated expertise and experience has been outlined in this paper. Because all testing data remains the property of the plant owner, only limited authorization has been gained to publish some of the data. Two case studies are demonstrated in this paper to give a general picture of what we have achieved in the past years.

As for the applications in auditing single phase measurement device and evaluating steam separation plant and purifier, the details cannot be provided in this paper due to lack of permission from the owners.

2. TRACER FLOW TESTING THEORY AND TRACER SELECTION

2.1 Review of tracer flow testing theory

Measurement of steam and brine flow and total enthalpy from each geothermal well is critical for management of the geothermal field and power generation. The main testing methods have been outlined by Bexley et al (2011). Among them the tracer dilution method is an optimal solution, due to its advantages of inline testing without interruption of plant operation and without requirement of heavy on-site equipment. The principle and method have been descripted in detail by Hirtz et al (1993, 1995), and Lovelock (2010).

The main principle is: composite liquid and steam tracers are injected into two-phase fluid pipelines at a constant rate, with tracers partitioning to brine and steam respectively. The tracers are then mixed with the steam and brine in the pipeline to become diluted. Samples are then collected downstream to get the tracers analyzed.

The tracer concentrations in the steam and brine can be used to determine the mass flow of the gaseous and aqueous phases in the pipeline. With the information of the pressure or temperature of the pipelines, the total enthalpy of the mixed fluid can be calculated. The equations given by Broaddus et al (2010) and Lovelock (2000) are as below:

$$Q_{L,V} = \frac{Q_T}{(C_T - C_B)}$$

Where $Q_{L,V}$ are brine and steam flow rates, Q_T, C_T and C_B are tracer injection rate, tracer concentration in the fluid and background respectively. All measurements are mass specific.

$$H_T = \frac{(Q_V \; X \; H_V) + (Q_L \; X \; H_L)}{(Q_V + Q_L)}$$

Where H_V and H_L are the enthalpies of steam and water at the pipeline temperature, which can be obtained from the steam table.

2.2 Tracer selection

Ideal tracers for practical application should meet the following criteria:

- The liquid and vapor tracers should partition completely into their respective phases, or the distribution between phases should be accurately known.
- The tracer must be chemically and thermally stable under the testing conditions.
- Precise analytical methods over wide ranges of concentrations must be available.
- The natural background levels must be low and constant.
- The equipment needed for injection and sampling should be simple and robust.

Many different tracers for liquid and steam have been studied and tested in the past two decades, some of which have been proved relatively ideal for practical application in the geothermal fields.

Steam tracers:

- Isopropanol: is in operational application in New Zealand and Iceland for many years. It has obvious advantages: cheap, safe, and easy to make composite steam and liquid tracers; detection limit as low as ppb magnitude with Gas Chromatography; simple and reliable to sample, no special containers and sampling skills are required. The disadvantage is that isopropanol does not completely partition into the steam phase, a considerable proportion of the tracer is dissolved in the liquid phase and the proportion is corresponding to the steam / water ratio. Therefore, when in practical application, the isopropanol concentration in the liquid must be accurately measured and be deducted from the steam tracer input as ineffective tracer.
- Sulfur hexafluoride (SF_6): is widely used in USA, New Zealand, Indonesia, Philippines and some other countries. It has excellent thermal and chemical stability and nearly completely partitions to steam phase. The detection limit is as low as PPT. Special vacuum flasks with sodium hydroxide solution and sample collection equipment and skills are required for the sampling. SF_6 is also a very bad greenhouse gas and is therefore banned in some countries.

Water tracer:

- Sodium Fluorescein: is used in Iceland. It is a good choice due to its excellent thermal and chemical stability under high temperature testing conditions. It has a very low detection limit and can be conveniently measured on site with a portable device. However, its existence in the background makes it less accurate.
- Sodium benzoate: is used in New Zealand during the past decade for geothermal flow testing. It demonstrates excellent thermal and chemical stability, easy and safe to make steam and water composite tracers. It is also very convenient to inject and collect samples. The downside is that costly, sophisticated instruments such as IC or uHPLC are required to make accurate analysis.
- Proprietary fluorescent compound is widely used in some countries. It is reported that except for its high thermal and chemical stabilities, it allows continuous onsite analysis.
- Sodium Naphthalene Sulfonates: is commonly used as reservoir tracer due to its excellent thermal and chemical stability. It can be used as liquid tracer, however its existence in the background reduces the accuracy and constrains its application.

3. TRACER TESTING EQUIPMENT

The tracer dilution technique has been used for geothermal flow testing for many years, but its accuracy and reliability remain uncertain if not properly controlled. Bexley et al (2011) reported that the accuracy of a properly controlled tracer flow test is about 5%. Based on our many years' experience, this figure is still too optimistic because of so many interference factors. The factors that interfere with the accuracy and reliability of a tracer flow testing results are listed below.

3.1 Tracer injection pump

Precision stoke type or inline type pumps are used for composite tracer injection into the pipelines. These pumps are supposed to have a precise and constant injection rate, while in practice, this is not completely true. Some injection pumps have better performance in a certain dosing range only. Poor performance might be obtained for very low or very high dosing rates. As a result, the calculated results can be greatly affected. As an effective quality control, regular workshop calibration and maintenance must be carried out.

3.2 Tracer injection probe

Tracer injection probe should be used whenever possible to inject the tracers directly into the mixed geothermal fluids. It can effectively prevent tracer from being leaked or retained. Care must be taken to ensure that:

- Injection probe is inserted deep enough into the main flow in the pipeline.
- No leakage or blockage at any connections.
- Regulation valves be fully open and not leaking.

It is obvious that any leakage or blockage from the probe can result in false injection rate, inaccurate mass flow and enthalpy calculation.

3.3 Scale and flow meter

Digital scales are used to measure the weight loss of tracers in a tracer testing. Annual calibration is minimal to maintain its accuracy. Careful handling during field operation is also important. Adverse weather such as wind and rain can also affect its performance in the field. It is observed that even light wind can greatly interfere with the scale and result in discrepancies and eventually inaccurate mass flow and total enthalpy.

Another interesting observation is that vibrating ground can greatly affect scale and makes it impossible to stabilize the reading. So, it is advised that digital scales should not be used near water pumps or other heavy machines.

Inline gas flow meters are vulnerable to even tiny liquid or solid in the gas flow. Careful handling and regular calibration are necessary to maintain their performance and accuracy. Otherwise, the testing results could be badly affected.

3.4 Tracer qualities

Nearly all the materials for making tracers are bulk factory products, not laboratory level pure. There might be some purity difference between different batches of supply. Every batch of tracer material supply should be checked for the effective gradient, to ensure the steam and liquid composite tracers have the accurate concentrations for effective gradients.

Some tracers are volatile, and the mixed composite tracers may have limited shelf life. It is important to make sure the composite tracers are mixed not long before the field testing starts. It is also advised that tracers should be properly stirred to get homogeneous distribution, so that a constant injection rate is guaranteed.

3.5 Sampling separators

Mini-separators are important equipment enabling collection of steam and brine samples from two-phase flow pipelines. They are commonly designed as a compact cyclone-type, taking in two-phase fluids at a limited rate and separating the fluid into steam and liquid by harnessing the gravitational and centrifugal forces. If properly controlled, mini-separators can achieve 99.9% separation effectiveness. In practical operation in the field, a lot of experience and skills are required to achieve a high steam dryness. In fact, significant contamination to steam and liquid samples is not unusual due to incomplete separation.

The consequence of contamination to steam samples by liquid or to brine samples by steam is that the samples are diluted to some extent and results in less tracer concentration, which will lead to inaccurate mass flow and total enthalpy. The contamination can be found by checking liquid tracer in the steam samples and steam tracer in liquid samples. For a properly controlled tracer test, liquid tracer should not appear in steam samples. Steam tracer concentrations in brine samples should be at a normal level (SF_6 should be nearly zero in brine samples). If excessive liquid tracer is detected in steam samples then the entire test could be ruined.

Some points should be followed to ensure a complete steam and brine separation:

- The sampling port should not be too close to a turbulent flow, which could make the separation less efficient.
- The sampling ports must be located on a horizontal pipeline with a reasonable length.
- Mini-separator should be positioned on a vertical sampling port on the top of the two-phase pipeline for steam; and near the bottom of the pipeline with an angle of approximately 45 degrees for brine. This arrangement is to make installing the separator easier and prevent debris in the flow from entering and blocking the separator and the cooling coils.
- The isolation valves to the mini-separators must be fully open to allow adequate fluid and to maintain sufficient pressures within the separators.
- The exhaust outlet flow rate from the separators should be properly controlled, so that the pressure drop from the separators are kept minimal, ideally no more than 0.2 bar.
- Manipulate the valves of the steam separator till a dry steam flow from the steam vent. The performance of the separator should be regularly checked to make sure the steam is dry during the entire test.
- A simple technique to find out if there is any steam mixed in the brine is to submerge the cooling coil outlet in cold water, the non-condensable gases will form bubbles if the sampling flow is contaminated by steam. But this technique doesn’t work very well in high-gas and high enthalpy geothermal fields.
- For cycling geothermal wells, a single mini-separator is not good enough to guarantee complete separation due to heavy surging. In this case a specially designed double-separator has achieved satisfactory results.
- Mini-separators should be regularly maintained and checked, to make sure they are thermally lagged and mechanically safe for daily operation.

3.6 Gas correction for mass flow and total enthalpy

Noncondensable gases are present in all geothermal discharges. Inline measurement equipment such as orifice plate and annubar can be significantly affected by the high proportions of NCG contained in the steam flow. The effect of NCG on tracer flow testing is not as severe as on the inline measurement devices, but if the gas proportion is significantly high, correction is still required to modify the steam and total enthalpy results. This correction can be achieved by accurately measuring the testing temperature instead of the pressure. If the NCG in the total flow is low, then the effect can be ignored.

Total solids in the brine tracer samples can influence the tracer concentration as well, resulting in less tracer concentration and overestimation of the mass flow. This influence however, is insignificant and can be ignored. More studies might be required to further quantify the effect.

3.7 Other considerations

Tracer dilution method is simple in principle but complicated in practical operation. More considerations are listed as below:

- The distance between the injection and sampling ports should be long enough to allow for adequate mixing of tracer with the total flow in the pipelines. Bends and inline valves may help with mixing.
- Sampling duration should be reasonably long to average the fluctuations caused by tracer pump strokes and well cycling.
- Every effort should be made to avoid contaminating the samples by unhygienic operation.
- Sampling flow should be reasonably high to get fresh inflow, which is more representative of the total flow.
- Sampling temperature should be kept under 30°C where possible to avoid vaporization.
- Sample should be preserved according to specific requirement to prevent tracer from precipitating or being absorbed to the walls of the containers.
- Sample containers must be kept air-tight and / or out of sunlight, to avoid volatile tracer vaporizing or degrading.
- Backup samples may be necessary in case the samples are lost or ruined during transport or analysis.
- Analytical results should be carefully checked. Re-analysis may be requested if the initial results are questionable.

4. CASE STUDIES

During the past decade we have conducted numerous tracer flow tests in New Zealand. A few of them are presented below.

4.1 NZK1

NZK1 is a production well in a liquid-dominated high temperature geothermal field in New Zealand. It produces two-phase flow at WHP of 15 barg. A series of PTS loggings were carried out after the well was completed. Figure 1 shows the temperature and pressure gradients measured in 40 days downhole logging. It is obvious that a section of isothermal has formed between 1000 m to 1180 m, indicating a convective interzonal flow and higher permeability. The hydrostatic pressure gradient indicates a single-phase liquid state in this section. It can be estimated from the measured temperature that the output total enthalpy of the well is about 1114 kJ/kg.

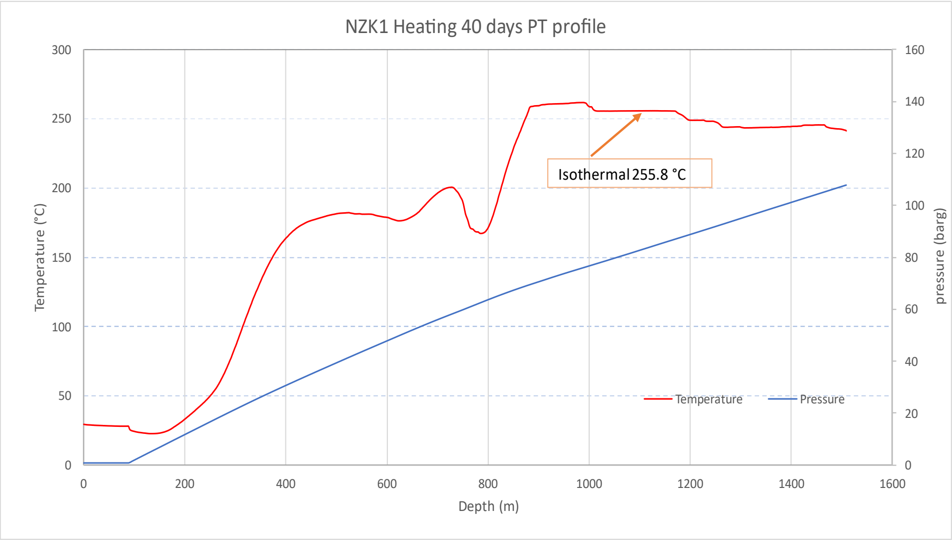

Figure 1. Temperature and pressure profile of PTS logging in 40 days heating

Comparing the mass flow measured with TFT and orifice plates, we can find that the TFT results are higher than orifice measured results from May 2019 to July 2020. From July 2020 onwards the TFT measured total flow was close to orifice measured results or slightly higher. Refer to Fig 2.

The total enthalpy measured by orifice plate and TFT shows a very interesting trend. The orifice measured total enthalpy is much higher than the inferred value of 1114 kJ/kg, and the general trend shows a gradual decrease. TFT measured enthalpy is slightly lower than the inferred total enthalpy, but the general trend is horizontal. All the measured data might indicate that the steam orifice plate has overestimated the steam flow and the fluctuation might be caused by scale deposit. The total enthalpy decline as measured by the orifice plate might be a false alarm. This conclusion can be supported by the TFT measurement. Further testing and more data are required to confirm this inference.

NZK1 is a good example that shows long term TFT is crucial to geothermal resources management.

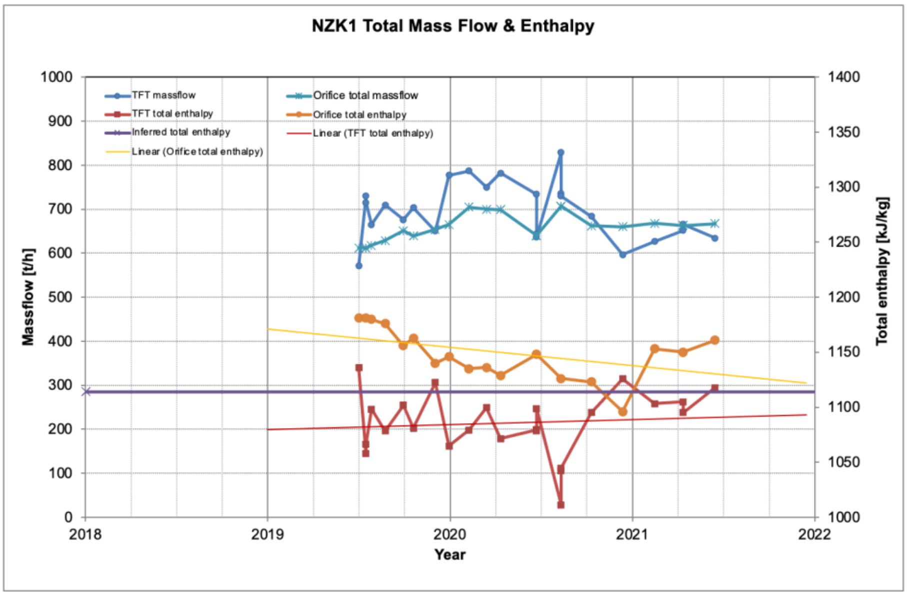

Figure 2: NZK1 Mass flow and total enthalpy with TFT and orifice measured results

4.2 NZK2

NZK2 is also a production well in a liquid-dominated high temperature geothermal field in New Zealand. It produces two-phase fluid at WHP of 10 – 15 barg. A downhole PTS logging was performed while the well was discharging at 246 t/h. The measured temperature and pressure are plotted as shown in Fig 3. A long interval of isothermal in the production zone indicated a 246.3°C single liquid flow. The inferred output total enthalpy is 1067 kJ/kg, obtained from the steam table. Refer to Fig 3.

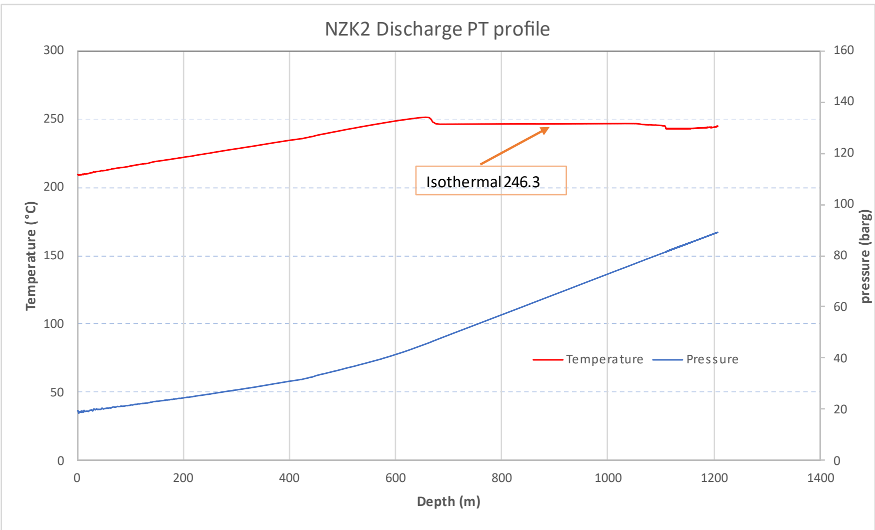

Figure 3: NZK2 measured temperature and pressure profile in the well using PTS tool during well discharge.

Figure 4 shows the TFT and orifice measured total mass flow and enthalpy as well as inferred total enthalpy from downhole PTS logging. The TFT total mass is slightly higher than the orifice measured value, but very close to each other. The TFT and orifice measured total enthalpy are also very close, but TFT measured total enthalpy is slightly lower.

ISSN 2703-4275

Both TFT and orifice measured total enthalpy indicate a declining trend, and the TFT enthalpy decline is steeper. It is likely that the well output has been declining very slightly. But due to the limited testing data, further data from both orifice and TFT are required to confirm the trend.

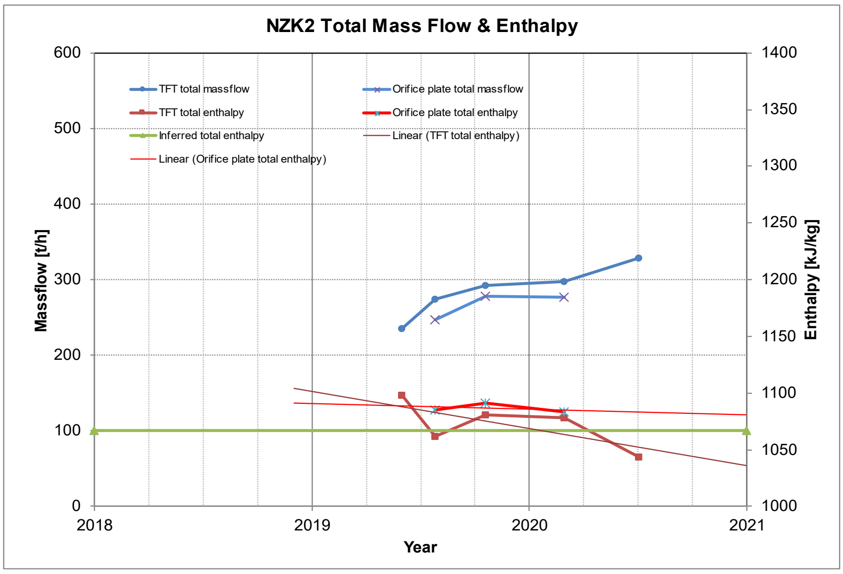

Figure 4: NZK2 Mass flow and total enthalpy with TFT and orifice measured results

4.3 Other applications with tracer dilution technique

Tracer dilution testing has been used for other purposes:

- Large diameter pipeline single phase brine flow measurement using tracer dilution was a success. Benzoic acid was used as the tracer. The measured flow rate was very close to the modelled value or orifice measured value.
- Measuring single phase geothermal steam flow in large diameter pipeline with tracer dilution has not been a success so far. The problem was probably a poorly controlled testing procedure. Better testing procedures are to be developed for further testing.
- Tracer dilution has been successfully applied to evaluating efficiencies of geothermal separation plants and purifiers. Multiple testing has proved its accuracy and reliability.

5. CONCLUSION

According to our experience in the past decade and reports from other sources, we can tentatively make some conclusions:

- Tracer dilution technique for geothermal flow testing is an important and effective tool for resources management.
- The accuracy and reliability of tracer dilution are not as good as surface output testing, but better than plant inline measurement devices.
- Even though every individual single test is not very accurate, long-term regular testing can provide important information on the geothermal reservoir behaviour.
- If properly controlled, SF_6 may be a better steam phase tracer than others.
- Both sodium fluorescein and sodium benzoate are good liquid tracers.
- More research may be required to develop a more accurate and more reliable testing system in the future.
- There is no standard method or procedure that suits all situations. Specific method and procedure must be tailored to each individual geothermal field or even individual well.

ACKNOWLEDGEMENTS

The authors wish to thank the management teams and staff of the geothermal power plants for their support and the permission to publish the data. Thanks also goes to the MB Century management team for their generosity of allocating time to complete this paper.

REFERENCES

Grant, M.A and Bixley, P.F: Geothermal Reservoir Engineering, second edition. 2011.

Lovelock, B.G: Steam Flow Measurement using Alcohol Tracers. *Proc. Geothermics Special Issue 30 (2001).*

Broaddus, M and Hirtz, P: Advancements in Tracer Flow Testing; Development of Real-Time Technology for Flow and Enthalpy Measurement. *Proc. World Geothermal Congress 2010* – Bali, Indonesia.

Hirtz, P.N and Lovekin, J.: Tracer Dilution Measurement for Two-Phase Geothermal Production: Comparative Testing and Operating Experience. *Proc. World Geothermal Congress 1995* – Florence, Italy.

Macambac, R.V and Troy A: Field-Wide Application of Chemical Tracer for Mass Flow Measurements in Philippine Geothermal Fields. *Proc. 23rd Workshop on Geothermal Reservoir Engineering, Stanford University 1998*– California, USA.

Aydin, H and Akin, S: Parameter Study on Tracer Flow Test. *Proc. 44th Workshop on Geothermal Reservoir Engineering, Stanford University 2019*– California, USA

ISSN 2703-4275