TESTING DIRECT USE GEOTHERMAL WELLS IN ROTORUA, NEW ZEALAND

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ABSTRACT

The township of Rotorua is located on top of a unique shallow geothermal system, which has enabled easy access to the resource and the utilization of several commercial and domestic direct use installations. However, there is no established standard methodology for the management of wells, especially in the way that they are tested and measured.

Down-hole testing and flow measurement are key factors in predicting and investigating the conditions and characteristics of geothermal wells. This study collects and uses data from all types of geothermal wells in order to classify their direct use.

There are several types of geothermal wells for direct use application in Rotorua, most of these wells are shallow bores <200 m deep with diameters of 100 mm, and 150 mm and commonly without liners. The types of direct use wells include self-discharge, down-hole pump, air-lift discharge, down-hole heat exchanger (production wells) and reinjection wells.

This classification is consequently used as the basis for recommending a standard methodology for conducting well test and production measurement, with the following objectives in mind:

- Determining the location of the feed zones, the well injectivity (well take).
- Productivity of the well (production test).
- Assessment of the performance of the well over time and monitoring the condition of the borehole.
- Scaling potential in the well

The data is also needed for monitoring reservoir conditions, assess the sustainability and investigating the environmental impact of exploitation of the geothermal resource for direct use of geothermal energy.

New temperature contour maps for the township of Rotorua were developed based on the available down-hole temperature data. Those illustrate the hydrology condition and geothermal regions in Rotorua. It will be of use when targeting new production wells and help decide the potential type of well for a given location.

1. INTRODUCTION

1.1 Background

More than 1,500 geothermal wells have been drilled in the shallow aquifer in Rotorua. Most of these occur in three regions. Rhyolitic domes in the north and south, and an ignimbrite layer at the bottom of the aquifer with an overlying sedimentary layer and the Rotorua sedimentary basin sequence (Steins, et al, 2012).

The wells extend from north to south of the city as shown in Figure 1. The wells are usually utilised by motels and hotels. The impact of the 1.5 km closure zone (The yellow dashed line) is immediately apparent with mostly down-hole heat exchangers (DHEs) located within this zone. The non DHEs in the zone are on limited term resource consents. When these resource consents expire the extraction of geothermal fluid must cease (BoPRC, 2005).

Figure 1: Distribution and density of geothermal bores across the Rotorua geothermal field showed by red dots and the yellow dashed line represents the 1.5km closure zone. (BoPRC, 2012).

2. DIRECT USE OF GEOTHERMAL ENERGY

Direct use of geothermal energy can vary enormously in scale and capital cost depending on the geothermal resource and type of applications.

The main advantages of using geothermal energy for direct use are low operational costs compared to fossil fuels, independent and direct control over the energy source and minimal environmental impact (Thain, et al., 2006). Direct use geothermal systems for space heating are very different to fossil fuel heating systems. This results in much lower operational costs. On the other hand geothermal direct use requires a relatively large initial capital investment (Lund, 1999) which involves drilling cost for production/reinjection wells and construction costs. Nevertheless, the overall economical advantages of direct use of geothermal energy are more favourable compared to fossil fuels.

The common technique for extracting the heat from a geothermal resource for direct use applications is by utilizing a heat exchanger to transfer heat from the geothermal fluid to the secondary fluid (Figure 2). The secondary fluid acts as a heat carrier and distributes the heat depending on its purposes.

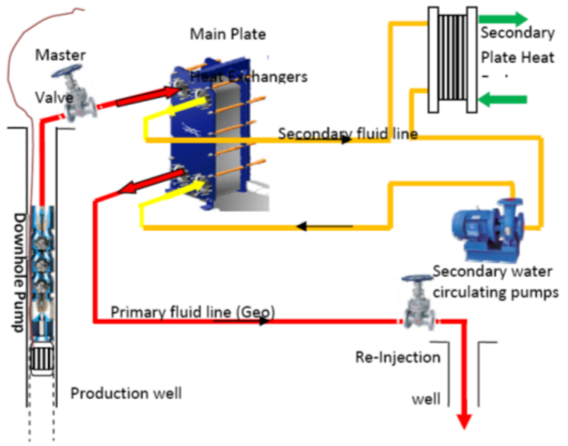

Figure 2: A schematic diagram of a typical system used in direct use of geothermal energy.

2.1 Classification of direct use geothermal wells

Direct use geothermal wells can be categorised based on the flow discharge rates of the well (Geothermal Resource Council, 1979):

- Irrigation wells (natural hot spring):
  Commonly deliver 60-125 l/sec geothermal fluid from shallow, low temperature aquifers utilizing pumps.

- Free flowing wells:
  Most included in these categories are wells which discharge geothermal fluid with flow rate of the 3-6 l/sec

- Deep geothermal wells:
  Wells drilled down to 1000 m, with pumping capacity of 60 l/sec. However, the flow rate of the wells is commonly in range of 30 l/sec.

The wells in Rotorua will be categorized in this study into three groups based on well capability and function.

1. Self-discharge (pressurized) wells;
2. Non self-discharge(non-pressurized) wells:
   i. Down-hole pump wells;
   ii. Down-hole heat exchanger wells;
   iii. Air-lift geothermal wells.
3. Re-injection wells.

2.1.1 Self discharging wells

Geothermal wells with water temperatures exceeding 150°C, are known to be self-flowing (Narasimhan and Witherspoon, 1979). Wells with self-discharge capability are commonly located in the up-flow zone e.g. in Kuirau Park, where well number RR 913 is used as a production well for geothermal direct use in the Rotorua Aquatic Centre (Figure 3), the wells at Rotorua hospital and Queen Elizabeth hospital.

Figure 3: Self discharge well (RR 913).

Reservoir pressure, rock permeability and depth of the feed zone play an important role in determining the capability of the well to self-discharge. Good permeability and high reservoir pressure will result in good production from a geothermal well with high temperature and enthalpy.

The self discharge wells observed in this study have temperature ranges from 145- 164^{o}C, which is categorized to be within the hot water temperature range (125-225 ^{o}C) geothermal systems (Kaya et al., 2011). These wells can transfers a significant amount of heat to the surface in the range of 3–30 MW thermal energy (Hochstein, 1990). Figure 3 show that the well has venting pipe to release non condensable gas (NCG).

2.1.2 Down-hole pump (DHP) wells

Geothermal fluid extraction using a down-hole pump is the common system for non self discharging geothermal wells. Down-hole pumps (Figure 4) are being used increasingly in low-enthalpy geothermal wells and low temperature geothermal systems (less than 125 ^{o}C) (Aksoy, 2007)

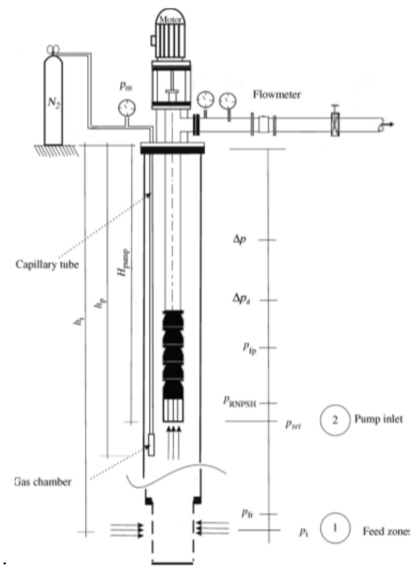

Figure 4: Diagram of a cased geothermal well in a down-hole line shaft pump (from Aksoy, 2007).

The installation of these pumps depends on the physical characteristics of the well, the chemical characteristics of the geothermal fluid, the production flow rate and the reservoir pressure and permeability (Aksoy, 2007). Two types of down-hole pumps: submersible and lines haft (top drive) are commonly utilized to produce the fluid.

An example is the well at Wylie Court Motel. It utilizes a DHP for well number RR 910 (Figure 5) for commercial use, water heating, space heating and laundry drying room.

Figure 5: Down-hole pump well (RR 910 in the Wylie Court Motel).

2.1.3 Air-lift discharge wells

Air-lift pumps (Figure 6) work by blowing air into the well using an air compressor. Hot water and air mix below the water level in the well. This consequently decreases the density of the hot water and as a result, the mixed fluids can be easily pushed out to be discharged at the surface for utilization.

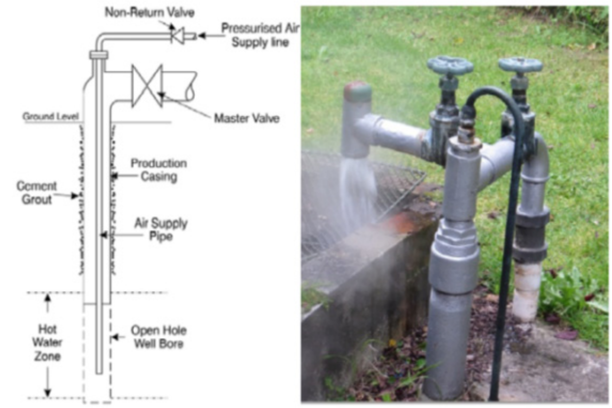

Figure 6: casing and wellhead details of an air-lift well (left). (Thain, et. al., 2006) and an air-lift geothermal well RR 447 (right).

The common problems with air-lift geothermal wells are deposition and corrosion fouling, which can occur due to the introduction of oxygen into the well. This will cause deposition in the inner surface pipe and later in plate heat exchangers. Drew (1988), recommended reducing the air ratio to raise the geothermal water flow to reduce these problems.

Air-lift geothermal wells are usually utilized in Rotorua for domestic purposes, such us bathing, mineral pool and heating system. The air-lift geothermal wells have a limited output, which makes this system more suitable for small scale domestic purposes that generally do not require large flow rates.

2.1.5 Spring take and discharge

Natural hot springs can be utilized for geothermal direct use. This is a traditional method in direct use of geothermal energy. This mode of use is more economical, as there is no need to drill a production well (Figure 7). It is also more environmentally friendly since hot water springs naturally discharge at the surface without the need for the geothermal fluid to be pumped or forced. However, a reinjection well for disposal of the hot spring water is necessary to prevent surface water contamination.

Figure 7: Concrete collection tank of hot spring water (S 952 in Holliday Inn, Rotorua).

2.1.6 Down-hole heat exchangers (DHE)

DHE’s are an environmentally friendly method of extracting heat from shallow geothermal wells. This is because using DHEs will eliminate the disposal of the geothermal fluid, since only heat is extracted from the well (Lund, 2003). DHE consists of a U-tube (Figure 8) or pipe laid inside the geothermal production well. Clean (fresh) water as a secondary fluid is circulated inside the pipe or tube, and the heat is extracted from the geothermal well by natural convection and conduction.

Installing the U-tube down-hole heat exchanger inside of the geothermal well is more economical compared with the other methods, because it does not require drilling a reinjection well, mitigates risk of scale deposition, pump maintenance costs.

DHEs would be very suitable for use within the 1.5 km exclusive zone around the Whakarewarewa thermal area (Figure 1) to avoid unfavorable environmental effects and maintain sustainability of the system.

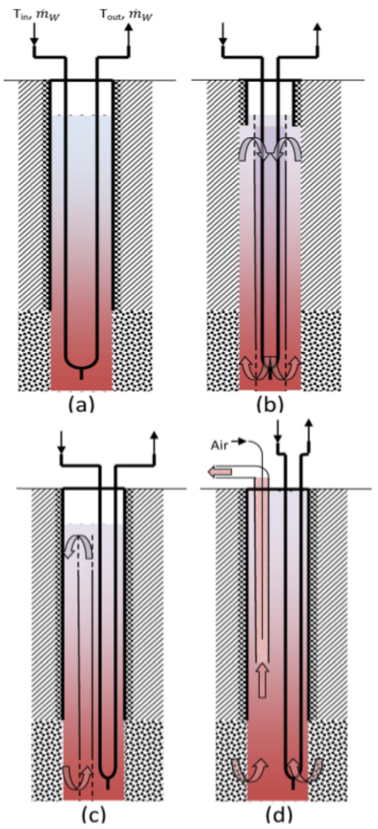

Figure 8: (a) DHE without a promoter, (b) DHE with promoter pipe (US design), (c) DHE with promoter pipe (NZ design), and (d) DHE with air-lift (from Steins, et at, 2012).

2.1.6 Reinjection wells

Reinjection wells are used to return geothermal fluid back into the reservoir after the heat has been extracted. This is done for environmental considerations as surface disposal of the geothermal waste-water is prohibited in most fields (Bodvarsson & Stefansson, 1988). Reinjection also benefits the geothermal reservoir by maintaining the pressure.

In this survey it was observed that, there are three methods for disposal of geothermal fluid in Rotorua:

- Reinjection into the shallow aquifer by reinjection well.
- Soakage in shallow aquifer.
- Discharging the geothermal fluid into a natural stream influenced geothermal water.

When disposing fluid from geothermal direct use wells, the following aspects should to be considered:

- The disposal of geothermal fluid by a reinjection well should be by using gravity. This will avoid the use of reinjection pumps as this can cause the vertical migration of hot fluid which can form hot springs at the surface surrounding the reinjection well at the surface (Kaya et al, 2011).
- The soakage system of geothermal fluid disposal should be in shallower wells and use a low flow rate for re-injecting the water.
- Reinjection of colder geothermal fluid can change the characteristic of the reservoir and causes scaling in reinjection pipe and/or in reservoir. In large amounts, colder geothermal fluid can cause thermal breakthrough at the production wells.
- A venting pipe to release non condensable gas (NCG) should be installed on reinjection wells.

In a highly exploited shallow reservoir such as in Rotorua, reinjection should be managed in case of thermal breakthrough and to maintain the reservoir. Stinger and Renner (1989) recommended the following guidelines:

1. In general, injection at lower elevation from the production well will tend to reduce thermal breakthrough impacts on the production wells.
2. It may be desirable or necessary to design the system so that the injection temperature matches the reservoir temperature at the point of injection.
3. Injection and production wells along a fault or fracture zone are likely to experience fast breakthroughs. The severity of the impact will depend on the rate of pumping versus relative fracture connectivity.
4. If injection at a higher elevation is necessary it would be desirable to inject into a different strata. This may not be possible due to reservoir conditions, cost, or environmental constraints. In this case allowance for fluid temperature degradation may be possible through increased equipment capacity or additional plates in heat exchangers or both to achieve closer approach temperatures.

3. WELL TESTING FOR GEOTHERMAL DIRECT USE.

The main purpose of well testing is to determine the well's characteristics and production capacity. The result is also used to interpret the condition of the geothermal reservoir, and is used as basis for decisions and policies relating to the sustainability of the resource and the environment of the geothermal system. Well testing begins during drilling and commonly continues as a monitoring program for the life of the well and reservoir (Kunze et al., 1979).

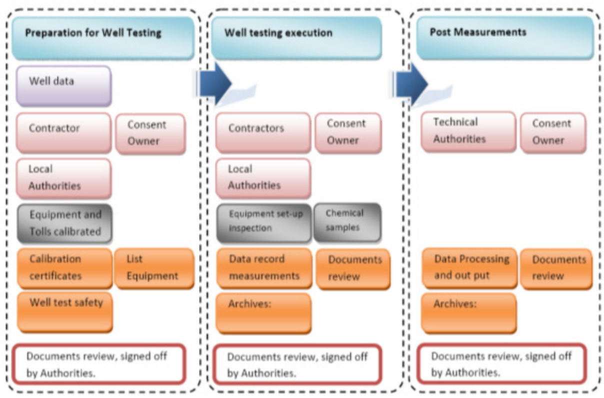

Figure 9: Latter stages of well testing delivery process for geothermal direct use wells.

Well testing can provide good information about the reservoir which can be used to determine the performance of the well and reservoir. It is also used to predict its behavior in the future. In areas with a high density of wells where every well is owned by a house hold or a company, conducting well testing periodically can develop into a monitoring program. Figure 9 describes the recommended stages for well testing and the participants.

The duration of well test depends on the accessibility of the well, environmental constraint and waste water drainage system at the test location. Overall, conducting a proper well test enables the accurate collection of flow rate, feedzone locations, fluid chemistry, scaling potential, temperature profile, and pressure or water level (Stiger and Renner, 1989).

The following are some of the techniques used for measuring geothermal well productivity.

3.1 Injection fall-off test

The simple description of an injection test was given by Houssein, et.al (2008). The injection testing in principle is the injection of water into a well while recording the flow rate and the changes in down-hole pressure or the water level in the well.

Injection testing is one component required to investigate reservoir and well properties such as injection zone and reservoir permeability.

In order to conduct an injection fall-off test, there are simple methods suitable for direct use geothermal applications, especially for wells with a bore-hole diameter less than 8 inches, as follows:

<u>a. Injection well with cold water</u>

Injecting cold water in order to determine how readily it will accept fluid. This method can also help cleaning up the well bore (Kunze et al, 1999). The time period for injecting the production well with cold water should be determined to avoid thermal breakthrough in the reservoir.

In theory, the injectivity period can be calculated with the equation below, which is used to calculate the time to reach radial flow:

Injectivity:

$$t_{radial\ flow} > \frac{(200{,}000+12{,}000.s).C}{k.h/_{\mu}} \quad (1)$$

$$C = V_w.c_{waste} \quad (2)$$

where:

- $t_{radial\ flow}$ = injectivity period (hour)
- s = the skin factor (estimate)
- C = the wellbore storage coefficient (bbl/psi)
- K = Permeability
- H = Reservoir thickness (m)
- M =kinematic viscosity
- J = Injectivity (ton/hr/bar)

The well test should not only reach radial flow, but also to sustain radial flow for a timeframe sufficient for analysis of the radial flow period. As a rule of thumb, a timeframe sufficient for analysis is 3 to 5 times the time needed to reach radial flow (Environmental Protection Agency (EPA), 2002).

Taking economic and operational factors into consideration, constant flow rate of injection could be done in 4 – 5 hours for an existing production well. This duration is in line with Kunze et al, (1999) who recommended that the duration is 1 – 3 hours in a short term test.

Recording the data during injectivity test is the key to success in well testing to obtain accurate record keeping. Therefore the synchronization times reported for injection rate and pressure data are a crucial part of the well test process.

<u>b. Injection falloff test</u>

The EPA (2002) regulation of the injection fall-off test states that a falloff test is a pressure transient test that consists of shutting in an injection well and measuring the pressure falloff over the same time period as the injection preceding it consequently. The time period is impacted by the magnitude, length, and rate fluctuations of the injection period.

Determining the time period for falloff test is given in the following (EPA, 2002).

Fall-off period:

$$t_{radial\ flow} > \frac{(170{,}000).C.e^{0.14.s}}{k.h/_{\mu}} \quad (3)$$

The result of the injection falloff test can be analyzed using several methods including Horner plot, semi log plots, log-log type curve and free water surface analysis (Kunze et al, 1999).

The pressure falloff test is conducted after the injection test, in which the well is quenched with cold water and it consequently warms up after the injection of the cold water has stopped. At this stage, the water level of the well bore decreases which is used to measures the permeability of the well.

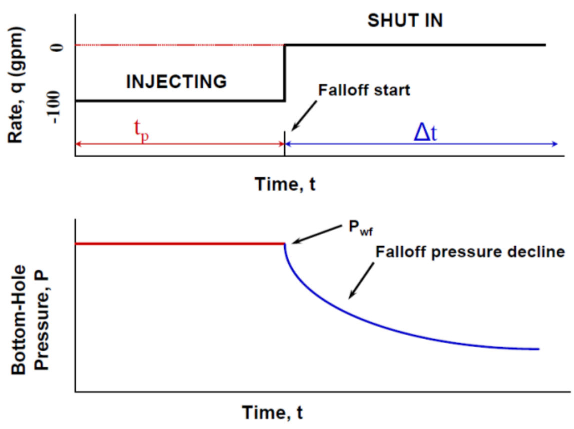

Figure 10. Injection Falloff Test Plotting Curve using single injection rate.

There are some considerations in conducting the fall-off test recommended by the EPA (2002).

1. Tag and record the depth of the water level in the test well.

2. Maintain a constant injection rate in the test well prior to shut-in. This injection rate should be high enough and maintained for a sufficient duration to produce a measurable pressure transient that will result in a valid falloff test.

3. Offset wells should be shut-in prior to and during the test. If shut-in is not feasible, a constant injection rate should be recorded and maintained during the test and then accounted for in the analysis.

4. Do not shut-in two wells simultaneously or change the rate in an offset well during the test.

5. The test well should be shut-in at the wellhead in order to minimize wellbore storage and after flow.

6. Maintain accurate rate records for the test well and any offset wells completed in the same injection interval.

c. Determining injectivity

During injection tests, the injectivity index (*J*) is often used as a rough estimate of the connectivity of the well to the surrounding reservoir (Houssein, 2008).

Injectivity tests are conducted by varying the injection pressure (p) and changing the injection flow rate (Q) as equation 4 below:

$$J = \frac{\Delta Q}{\Delta p} \quad \ldots \ldots (ton/hr/bar) \qquad (4)$$

Some of the considerations that should be managed and prepared prior to operational testing are:

- Surface facility constraints, which relates to the capacity of injection water and adequate waste storage or drainage system.
- Offset well considerations.
- Record keeping to maintain an accurate record of injection rates and real time record.
- Well calibrated and sound condition of instrumentation and pressure gauges.

Figure 11 shows a schematic diagram for the injection falloff test set up.

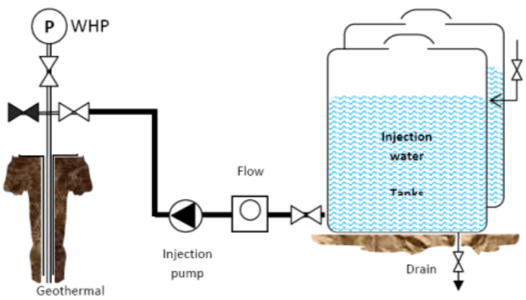

Figure 11: Simple Injection Falloff Test Set-Up.

3.2 Temperature profile measurements

The temperature profile of the well can be conducted by simple tools, such as down-hole thermometer/thermocouple with a string cable complete with tape measure. By running the thermometer for the full depth of well, the temperature in each meter depth can be recorded.

The multi run temperature measurement, as in Figure 12 is a common method used to estimate the condition of the borehole and determine the feed zone. This is conducted several times such as during the heating up time, injecting with colder water, shutting and discharging the well at different well head pressures

The permeable formation and the feed zone at the reservoir can be identified from the temperature profile. Temperature profile measurement can be used to determine these zones after the injecting of cold water into borehole. This method is commonly used to determine the entry zone of hot water from the reservoir (Kunze et al, 1989).

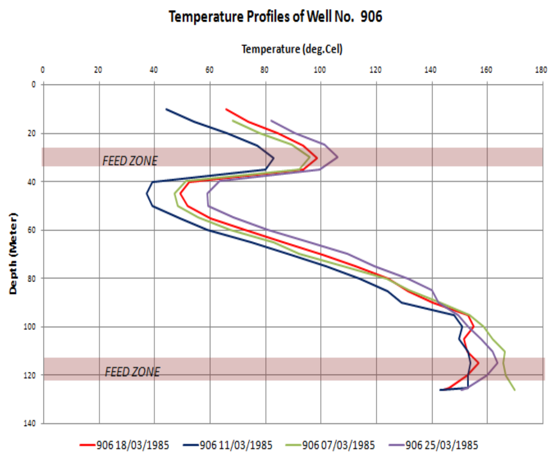

Figure 12: Multi run temperature warm-up profiles.

3.3 Flow rate measurement (output discharge) test.

In a direct use geothermal well, the process can be summarized into five methods of production testing:

3.3.1 Vertical discharge

This technique of measurement is used in an empirical correlation to calculated flow rate. However, vertical discharge measuring the enthalpy of fluid based on the fluid enthalpy at the main zone temperature should be considered (Helbig & Zarrouck, 2012). Determining the mass flow rate can be described with the Russell James formula.

The vertical discharge test cannot be conducted in Rotorua city, due to environmental factors like high noise and the generation of undesirable steam plumes in the city.

3.3.2 Total flow calorimeter

The total flow calorimeter is commonly used in direct use geothermal well with a maximum flow rate of approximately 10 kg/s and a maximum enthalpy of 950 kJ/kg (Helbig and Zarrouck, 2012; Sitonen, 1986).

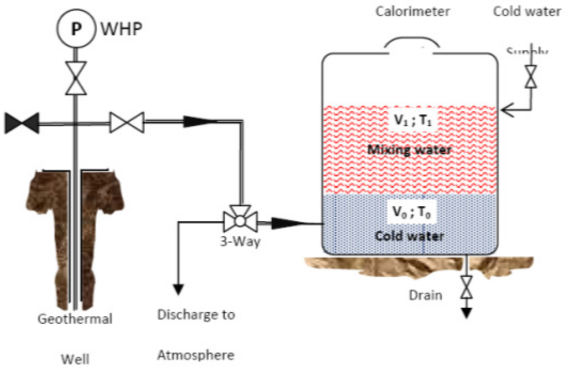

Figure 13: Schematic diagram calorimeter set-up (modified from Sitonen, 1986).

The total flow calorimeter can be used to produce an output curve for the well by carrying multiple tests with different control/side valve settings. The output curve can be used to estimate the production flow rate and enthalpy from the running WHP. The output curve should be re-measured every two years.

There are several disadvantages in this method, such as it requires mobilization and demobilization of the truck or trailed mounted calorimeter. Other notable disadvantages are:

- Heat lost from the sides of the tank to the atmosphere.
- The size limitation of the tank because the tank should be portable.
- Water may splash out of the tank due to flow.
- Steam may be lost from the tank.
- The size of piping from the well may restrict the flow rate.

Over all, even though the total flow calorimeter has several disadvantages, this method is an adequate way to measure flow rate of self discharge geothermal well for direct use application.

3.3.3 Plotting pump performance curve

Existing down-hole pumps can be used for conducting well test and measurements, especially for production capability. By using the pump performance curve, the production flow rate based on the known well head pressure P_1 can be easily determined, as shown in Figure 14 below.

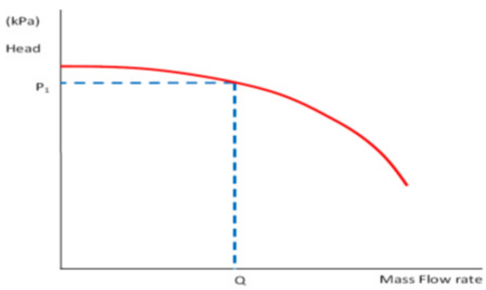

Figure 14: Example of a characteristic pump performance curve for constant speed and fixed diameter of the pump impeller.

3.3.4 Count filling time with a bucket and stopwatch

The flow rate of a production well could also be measured using a small water vessel of a known volume and stop watch to measure filling time. This method is feasible for measuring low enthalpy production well. It was conducted during this study at RR 447 with its air-lift discharge geothermal well. This method is a simple way of flow rate measurement for a low production rate geothermal well and direct use application in domestic purposes.

3.3.5 Weir box measurements

Measurement of flow rate using a weir box is a simple method with good accuracy. There are many types of weir box based on the shape of the discharge side of the well (Figure 15). The different shapes of the weir box have different correlations to determine the flow rate. Below are some equations to determine flow rate in each type of weir box (Simplified for water at 98°C):

- Rectangular weir $m_w = 6000\ x\ b\ x\ h^{1.5}$ (5)
- 90o – V notch weir $m_w = 4720\ x\ h^{2.5}$ (6)
- Suppressed weir $m_w = 6290\ x\ b\ x\ h^{1.5}$ (7)

Figure 15: Typical weir box with several types of discharge shape side.

3.4 Geothermal fluid chemical sample

Taking fluid samples of a geothermal well is key to monitoring the characteristics of the fluid chemistry from the reservoir. Based on the chemical properties including its gases and dissolved solids, its behavior at different temperatures and pressures can be determined which is required to assess scaling potential. This test is usually conducted when the geothermal fluid will be disposed of in a reinjection well. A small port sized 0.5- 1.0 inch should be provided near the well head for chemical sampling (Figure 16).

Monitoring surveys of fluid chemistry commonly performed as shown in Figure 16, at a minimum of once every two years for production wells.

Kindle (1989) described five different factors that affect the accuracy of analytical determination of geothermal fluids:

1. Flow composition shift with time from the well.
2. Differences in sampling methods.
3. Sample stabilization processes.
4. Different analytical methods.
5. Differences between laboratories using the same methods.

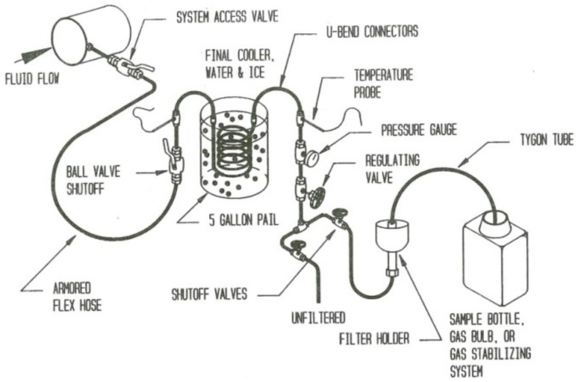

Figure 16: Geothermal fluid sampling equipment and arrangement (from Kindle, 1989).

3.5 Casing condition survey

The production casing in a geothermal well is the primary conduit for the production of fluids from the formation to the surface. Thus it is subjected to extreme conditions from thermally induced stress conditions and from continuous exposure to formation fluids both internally and externally (Hole, 2008). Therefore, the production casing condition should be surveyed periodically to monitor the well condition and to ensure the safety of the well. There are some problems which could occur on the production casing during its operation such as scaling, thermal deformation, collapse and internal and external corrosion.

The first approach to identify any issues is to run a down-hole measurement using a Go-Devil (which allows internal well diameter assessment). This could be followed by a mechanical (multiple-arm) caliper. It measures the inner diameter condition of the geothermal well casing more accurately. However, the limitation of the mechanical caliper is the size. The smallest size of a mechanical caliper is 4 inches in diameter. As a result, a geothermal well which has a diameter smaller than 4 inches cannot be measured by running a mechanical caliper to survey the condition of its inner casing. However running a Go-Devil is the appropriate method for direct use geothermal wells. It can be conducted regularly every two years for any diameter well. The Go Devil tools have a large range of diameter sizes and are more economical.

4 TESTING DIRECT USE GEOTHERMAL WELLS

A number of techniques in well testing and measurement are described. The testing is adjusted for direct use geothermal wells in Rotorua according to the well data. The wells are categorized depending on their type and use.

4.1 Self discharge wells

Steps to measure self discharge geothermal well in direct use application:

i. Injectivity falloff test (optional)

ii. Casing condition survey by running Go Devil tool

iii. Temperature profile measurements

iv. Flow rate measurement by total flow calorimeter

v. Geothermal fluid chemistry samples

4.2 Down-Hole Pump (DHP) Wells

For an existing well setup, the complete set of down-hole pump and its accessories should be pulled out from the well in order to measure temperature profiles and conduct an injectivity falloff test. After conducting both of these tests, the down-hole pump set can be reinstalled in the well to conduct flow rate measurement and take a fluid sample.

Steps for well testing for DHP geothermal well:

i. Casing condition survey by running Go Devil tool should be run first before any expensive tools go into the well bore also testing during the life of the well is recommended.

ii. Injectivity falloff test (optional)

iii. Temperature profile measurements

iv. Flow rate measurement.
(Determining the flow rate can be done by plotting wellhead pressure on the pump performance curve).

v. Geothermal fluid chemical sampling

4.3 Air-lifts discharge wells

Most geothermal wells at Rotorua (which use air-lift to extract hot water) have a lower production rate than the other types of well. This is due the air-lift well limitation in pulling out water with pressurized air in a vertical pipe. The sequences for this type of well are as follows:

i. Casing condition survey by running Go Devil tool.

ii. Injectivity falloff test (optional).

iii. Temperature profile measurements.

iv. Flow rate measurement can be conducted by:

- Bucket of water and counting filling time;
- Measuring discharge water levels at the weir box.

i. Geothermal fluid chemical sample test once every year

4.4 Down-hole Heat Exchanger (DHE) wells

DHE well do not discharge geothermal fluid. Therefore the production output cannot be directly measured and there are additional measurements of heat extracted.
The steps for well testing are as follow:

i. Injectivity falloff test (optional)

ii. Temperature profile measurement

iii. Extracted heat test
DHE geothermal wells extract heat from the reservoir indirectly. The extracted heat should be measured. This can give insight as to how the optimum heat that can be produced from the well by adjusting the flow rate of secondary fluid. The simple method of an extracted heat test is to measure the secondary fluid discharge temperature at several flow rates, by using equation 8 below:

$$\dot{Q} = \dot{m}(h_{hot} - h_{cold}) \quad (8)$$

Flow rate against transferred heat as the heat output can be plotted (Figure 17).

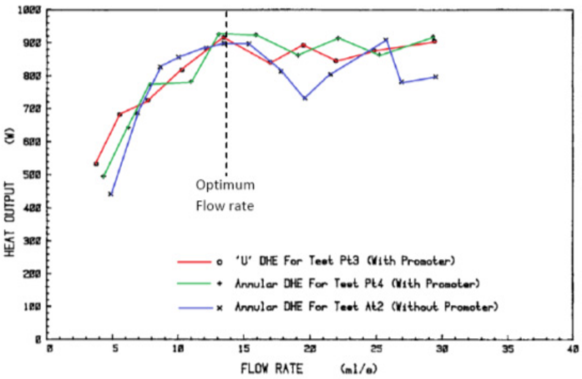

Figure 17: A typical graph of flow rate against heat output (Freeston and Pan, 1985).

This method is appropriate for simple U-tube DHE's and DHE's with promoter pipe. Two parameters of DHE with airlift should be determined. The optimum flow rate of air blown into the well and the optimum flow rate of secondary water that gives the maximum heat output. This method is practically the same, but two parameters are plotted and the optimum point is found in the same way.

iv. Casing condition survey (optional). This stage is an optional test due to the complicated setup in the DHE well.

4.5 Reinjection wells.

Testing and measuring of reinjection well is also essential in order to manage and monitor the conditions of the reservoir. Below is the methodology for its testing and measuring:

i. Injectivity falloff test (optional)

ii. Measurement of temperature profile

iii. Casing condition survey

iv. Geothermal fluid chemical sample test.
The geothermal fluid from the production wells and fluid which is to be disposed into the reinjection wells have physical and chemical composition differences. Taking these differences into consideration, extraction of sample fluid before returning it back to the reinjection well also provides.

v. The differences of fluid characteristics from the production to reinjection well are due to the following reasons:

- The difference in fluid temperature.
- The geothermal fluid is introduced with air for air-lift discharge well.
- The geothermal fluid is mixed with other fluids during processing for heating or for mineral pool.

vi. The recommendation is sampling geothermal fluid a minimum of once a year.

- Casing condition survey.

4.6 Hot Spring take and discharge

Utilizing hot springs for direct use do not require a well, or a reinjection well. In order to dispose of the hot water after use it can be discharged to the local stream. Therefore, methodology measurement and testing is different from the other methods.

Below are sequences of testing and measuring production for hot spring take and discharge for direct use:

i. Measuring the average temperature of the spring

ii. Flow rate measurement. Measuring the production capacity of hot springs for direct use can be conducted using the existing pump that is used to take geothermal water from the hot springs. The methodology at this stage is similar to measuring the flow rate of a geothermal well with a down-hole pump to extract the hot water from the well.

iii. Geothermal fluid chemical sample is taken once a year.

5. TEMPERATURE CONTOUR MAPS OF ROTORUA.

Down hole temperature data from 161 wells data measured by the Bay of Plenty Regional Council from 1953–2011 (82% measured in 1980s) were used to get representative temperature contours of the geothermal resources in Rotorua township. The wide range of dates for the measurement of the temperature profiles gave a distribution of the shallow hydrothermal conditions in Rotorua.

The temperature profiles were then contoured (Figures 18-21) to develop an idea of the subsurface Rotorua hydrology condition. The plots show the main up-flow zones at Whakarewarewa thermal reserve, Kuirau Park and Paurenga Park. These are the three main up-flow zones in Rotorua, and indicated as temperature maxima at about 100 m below the surface (Steins and Zarrouk, 2012). The out-flow zone lead from the up-flow zones to lake Rotorua and mainly discharge into Pauranga stream around the sulfur bay.

The temperature contours at 250 mrl (Figure 18) and 275 mrl (Figure 19) are the shallow part of ground subsurface, the depth around 0 – 50 m below the surface, showing areas of hot spots around the thermal manifestation such us in Whakarewarewa thermal area, Kuirau Park and sulphur bay. The cooler areas are indicated in yellow to green.

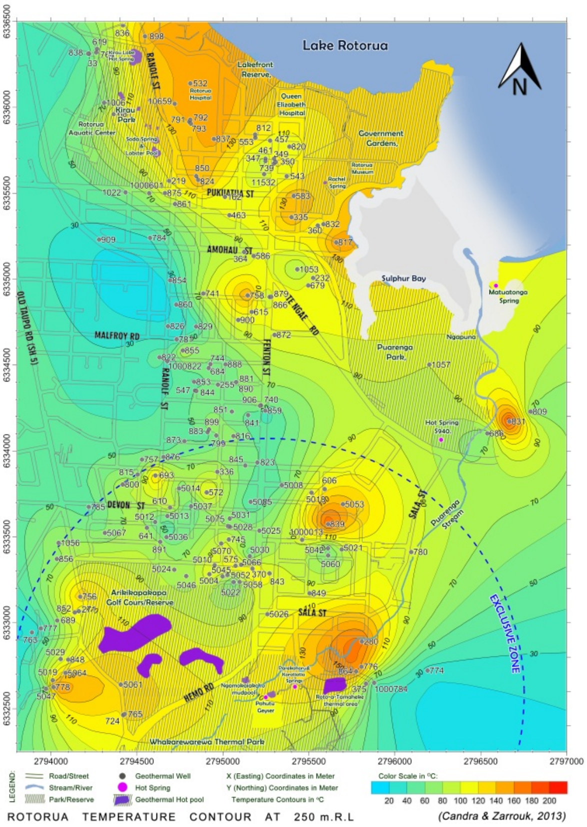

Figure 18. Temperature contour maps at 250 mrl.

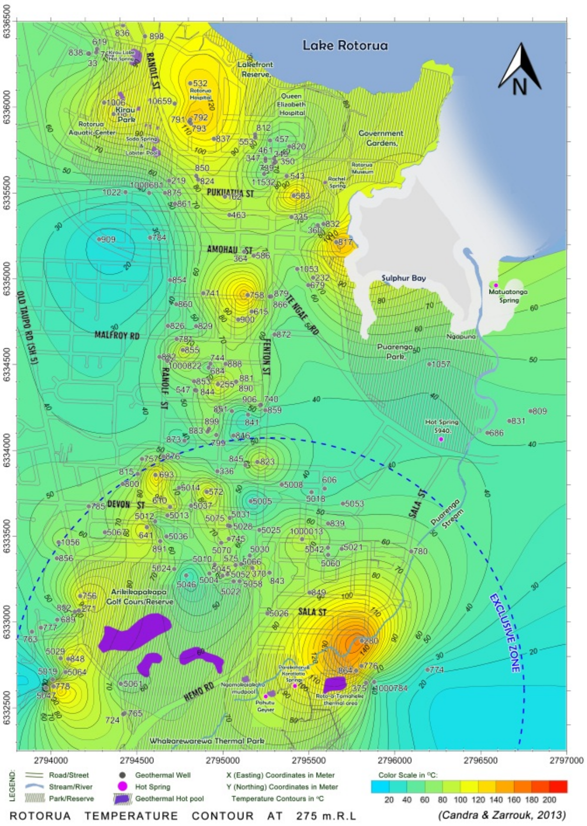

Figure 19. Temperature contour maps at 275 mrl.

Figure 20 and Figure 21 also show an interesting area between Fenton and Ranolf streets where well numbers 845, 336, and 823 are located; at the border of the exclusive zone. This area exhibits colder ground compared with the surrounding wells. This indicates wells do not self-discharge and further investigation did not show that area is used for reinjection.

Contours below 100 mrl are not representative of the actual condition, due to the limited information in the 200 – 250 m depth range (the average well depth in Rotorua is around 130 m from ground surface).

Most of wells in the up-flow and out-flow zones can self-discharge which have temperatures of geothermal fluid of around 150–200^o C. They show characteristics of liquid dominated fluid such as that seen at Rotorua Aquatic center, Rotorua Hospital near Kuirau Park. These wells are located in the dark red area in Figure 22. The light red area located in the exclusive zone also indicates self-discharging wells. However, in order to utilize the heat, DHE are required.

The wells in the yellow area of Figure 22 have temperature (above 80^o C). However, these wells do not self-discharge.

The blue area of Figure 22 indicates non-self-discharging wells here warm temperature below 80 ^{o}C can be encountered. Consequently, in order to extract the geothermal fluid in the yellow and blue areas: down-hole pump, down-hole heat exchangers or air lifting will be required.

It is important to note that the well zones of Figure 22 were determined based on the reported production history of these wells. This zoning will make well siting relatively easy for geothermal direct use developer/user and can potentially help the local regulator to formulate policies for the different types of geothermal wells in the future.

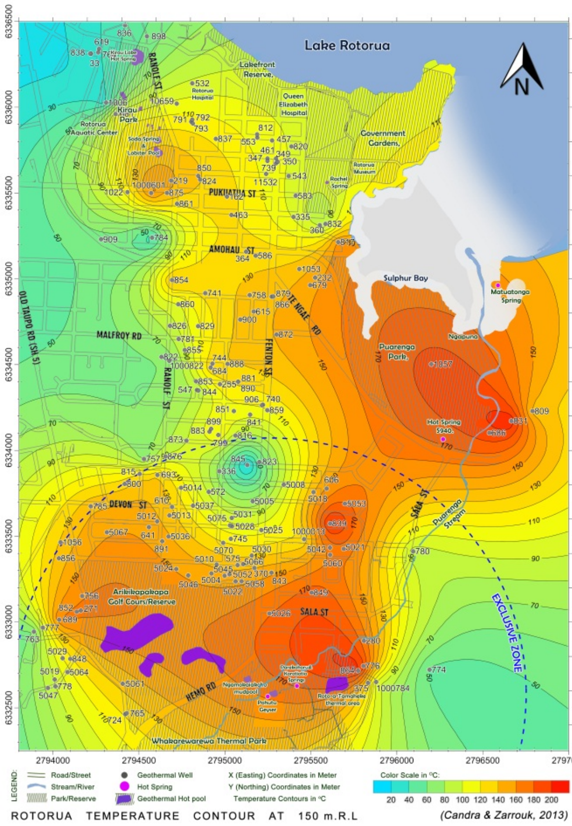

Figure 20: Temperature contour of Rotorua at 150 mrl.

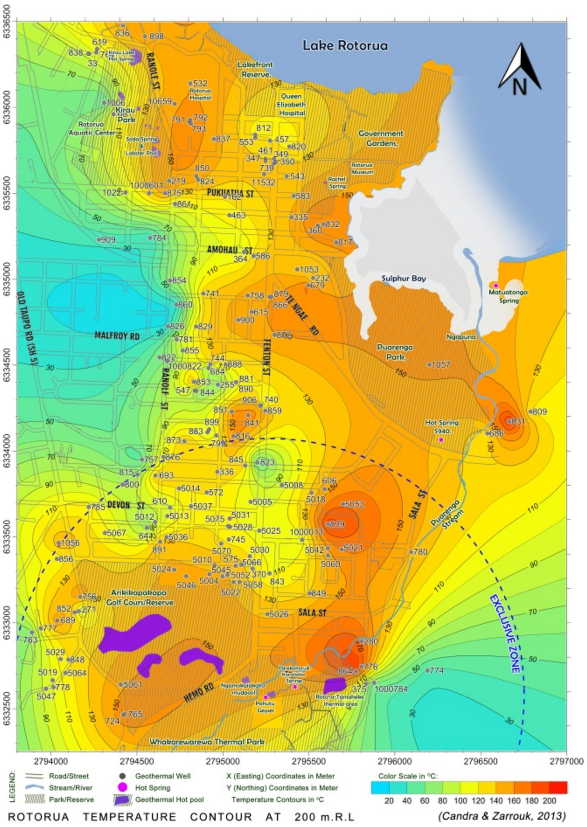

Figure 21: Temperature contour of Rotorua at 200 mrl.

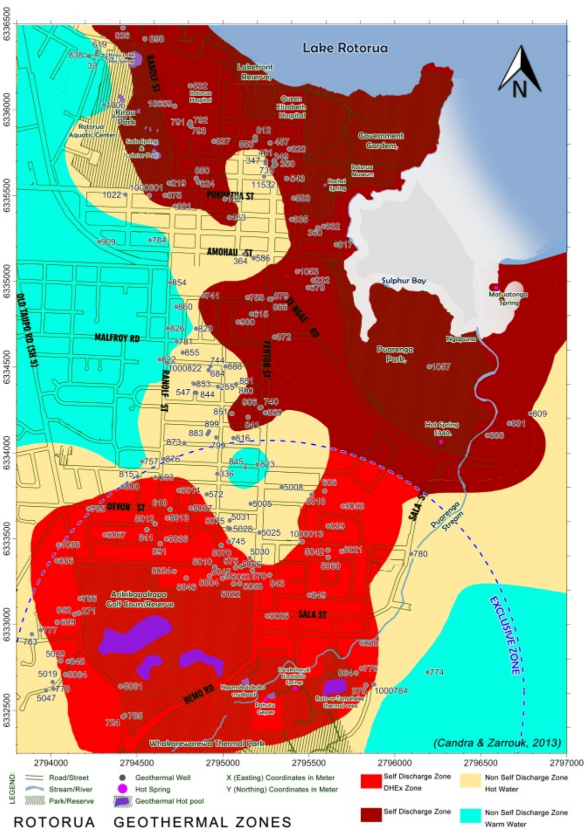

Figure 22: Different direct use well zones in Rotorua.

6. CONCLUSIONS

Well testing and measurement for the different types of geothermal wells is required at different stages of its use. Table 1 gives a summary of the recommended methodology for testing these well.

The well testing methodology is to assess/measure the production capacity and monitor its long term behaviour for each type of wells. Ultimately, the result will be used to monitor and manage the geothermal resource in Rotorua. Perhaps in the future, upon standardization of well testing and regular evaluation, annual representative data can be obtained.

The results of the well testing can become a reference for both the regulator and the developer of direct use geothermal energy. There could be a requirement for well testing prior to issuing new concession or renewing an existing one for direct use. This will also stand as a reference point in order to help define policies for the area and to sustainably develop and utilize the geothermal resources.

A new map (Figure 22) was developed for the township of Rotorua, showing the potential type of wells expected within city.

	Self discharge wells	DHP Well	Air-lifts discharge wells	DHE wells	Reinjection wells	Spring take & discharge
Injectivity falloff test	Opt.	Opt.	Opt.	Opt.	Opt.	N
Temperature profile measurements	Y	Y	Y	Y	Y	Y
Flow rate measurement (output discharge) test	Y	Y	Y	Y	N	Y
Vertical discharge	N	N	N	N	N	N
Total flow Calorimeter	Y	N	N	N	N	N
Weir box	N	N	Y	N	N	N
Bucket and stopwatch	N	N	Y	N	N	Y
Existing pump performance curve	N	Y	N	Y	N	Y
Extracted Heat test	N	N	N	Y	N	N
Geothermal fluid Chemical sample test	Y	Y	Y	N	Y	Y
Casing condition Survey with Go Devil tool	Y	Opt.	Y	Opt.	Y	N

Note: Y = Yes; N = No; and Opt. = Optional

Table 1. Summary of the recommended methods of measurement for the different types of wells.

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