Well Testing Program to Determine Well and Reservoir Characteristics

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Exploration Drilling and Early Stage Geothermal Reservoir Characterization
ITB Geothermal Workshop
Bandung, Indonesia

4-5 March, 2013
Objective

- Present and discuss the tests/surveys that are normally included in a well testing program during exploration/early stage geothermal development to characterize the well and reservoir conditions
  - Actual program will be project specific and based on local conditions and constraints
  - The tests and surveys that will be discussed are not “new”; they have been used and refined by reservoir engineers in the geothermal industry over many years
  - References are provided that contain additional background information and further details on some of the examples shown
Outline

- Basic Principles
- Potential Challenges
- Tests / Surveys and Timing
  - Wireline Survey Equipment
- Testing During Drilling
- Completion Injection Tests
- Shut-in Surveys During Well Heat-Up
- Well Flow Testing
- Multiple Well Flow Test
Basic Principles

Testing program required to:

- Define individual well characteristics
- Provide information on the reservoir for development of conceptual and numerical models
Basic Principles

- Cannot “see” the geothermal reservoir to directly measure reservoir parameters
  - Pipeline on open ground – we can measure diameter, length, pressure drop and flow
  - Pipeline through a hill – we can measure flow and pressure drop but need to assume diameter and/or length or develop a testing procedure to determine the unknown parameters
Basic Principles

- Need to infer reservoir parameters from information obtained from the wells which are our “eyes” in the reservoir

- Well test program is designed to provide information on:
  - Location of permeable zones within the well
  - Temperature, pressure and thermodynamic conditions (water, two-phase, steam)
  - Well and reservoir permeability characteristics
  - Well discharge characteristics
    - Mass flow rate and enthalpy (heat flow)
    - Steam, water and gas chemistry
Basic Principles

- Well test program generally consists of a combination of surface and sub-surface tests and surveys.
- Aim is to develop models of the wells that can then be used to construct conceptual and numerical models of the reservoir.
  - Requires integration of the well test data with all other available data (geology, geophysics, geochemistry, drilling data, etc).
Potential Challenges

- Many exploration projects are now in remote locations with under-developed infra-structure
  - Significant up-front costs to upgrade or build new roads, bridges and facilities
  - May need to consider slim holes rather than full size production wells for initial exploration to reduce costs but this may restrict the information that can be obtained particularly from flow tests

- Environmental and cultural sensitivities
  - Will impact the project cost and possibly the scope of the well testing program, particularly flow testing
  - Injection well will likely be required to dispose of produced fluids; at least two wells will be required before any medium or long term flow testing can be conducted
Tests/Surveys and Timing

- **During Drilling (in addition to MWD Data)**
  - Static Formation Temperature Tests (SFTT)
  - Pressure and temperature surveys
  - Pressure while Drilling (PWD)
  - Flow testing and/or injection testing
  - Geophysical logs (Fracture identification, Natural Gamma, etc)
  - Coring (continuous, short or sidewall)

- *Cost and risk to the well need to be carefully considered but may be justified for exploration*
Tests/Surveys and Timing

- Injection Tests at Well Completion
  - Multi-rate injection tests
  - Pressure/Temperature/Spinner (PTS) surveys
  - Pressure transient tests (pressure falloff, multi-rate)

- Shut-in Pressure/Temperature (PT) Surveys
  - Conducted at regular intervals to monitor well heat-up (eg. 1, 3, 6, 12, 24 day shut)
Tests/Surveys and Timing

- **Individual Well Flow Testing**
  - Techniques to initiate flow
  - Flow, enthalpy and chemistry measurements vs wellhead pressure and time
  - Flowing PTS surveys
  - Pressure buildup test

- **Multiple Well Flow Test**
  - Flow at higher production levels than single well test and measure the effect on the reservoir
    - Requires production, injection and observation wells
  - Tracer tests to determine the interconnection between injection and production wells
Wireline Survey Equipment

- Wireline
- Sheave
- Lubricator
- Wireline or Cable
- Winch
- Survey tool
- BOP
Wireline Survey Equipment

Lihir Island
Papua New Guinea (1986)
Wireline Survey Equipment

Pressure/Temperature/Spinner (PTS) Tool
Dieng, Indonesia (1987)
Wireline Survey Equipment

Electric Line Winch Truck
Tiwi, Philippines (2008)
Testing During Drilling

Static Formation Temperature Tests
Downhole Pressure Surveys
Pressure while Drilling
Static Formation Temperature Test (SFTT)

- Can provide information on static reservoir temperatures
- Analysis assumes formation is cooled conductively by circulation of drilling fluids
  - Best results obtained with full circulation
- Heat-up is monitored after some period of circulation and analyzed to provide estimate of static reservoir temperature
- Requires 12 to 24 hours of rig time and is run in open hole; need to consider cost and risk
Number of analysis techniques in literature that provide corrections to the basic “Horner” method and the method developed by Brennand (1984) has proven to be reliable and easy to use.

\[ t_p = \text{circulation time} \]
\[ \Delta t = \text{time since circulation stopped} \]
Downhole Pressure/Temperature Surveys

- Conducting repeat downhole pressure and temperature surveys may provide information on how conditions are changing as the well is being drilled.
- This may be useful if there are zones in the reservoir that are not well connected and are therefore not in equilibrium.
- Once well is completed, “cross flow” (upflow or downflow) may occur and it may no longer be possible to measure the true in-situ conditions.
Pressure Changes with Depth
*Dench (1982)*

If well is open to both the “perched” aquifer and the geothermal reservoir, downflow will occur due to the difference in pressure.
Data is collected from pressure sensors located in a sub in the drillstring near the bit.

Pressure drops indicate locations of permeable zones while the magnitude of the pressure change provides indication of how permeable the zone is.

In this example, a number of permeable zones have been identified, with the major zone at 3,500ft.

*Tool is expensive and the cost and risk of getting stuck needs to be evaluated vs the value of information obtained.*
Completion Injection Tests

Pressure/Temperature/Spinner (PTS)
Multi-rate Injection Tests
Pressure Transient Tests
Injection Tests at Well Completion

- A series of tests are conducted to determine the location of permeable zones and to provide an estimate of the well’s permeability

- Tests include:
  - Temperature or PTS surveys while injecting
  - Multi-rate injectivity test
    - Obtain “Injectivity Index“
  - Pressure transient data analysis
    - Estimate “transmissivity” and “skin” factor from analysis of pressure falloff (PFO) and multi-rate data
Typical Completion Test Program

- Start pumping at 30 bpm, rig-up (1 hr)
- 2 or 3 PTS stationary logs inside 7” liner (50 mins)
- Place tool at II depth (10 mins)
- Multi-rate injection test (4 hrs)
- Pressure stabilization (50 mins)
- Place tool at II depth (10 mins)
- PTS down log, up log (55 min), (55 min)
- Place tool at top (10 mins)
- PTS stationary log at bottom (5 mins)
- PTS stationary log at top (5 mins)
- 2 or 3 PTS stationary logs inside 7” liner (50 mins)
- PFO (4 hrs)
- PTS up log (1 hr)
- Rig down (1 hr)
PTS/Temperature Surveys While Injecting

- Surveys are run while injecting water at two different rates, if possible
  - max (≈30bpm) and 10-15bpm

- Purpose is to locate the permeable zones from the temperature and spinner responses
  - May see different responses at the two rates

- Where injected water is flowing, temperature is low

- Where there is no flow, water is heated by rock and temperature increases

- Can have many different situations if multiple permeable zones are present
Temperature Profiles While Injecting

- Single zone at TD
- Single zone within well
- Two zones accepting
- Two zones one inflowing

Increasing temperature
Injecting PTS Survey, Bul-104 (Mak-Ban)

Increasing temperature as fluid leaves the well
Multi-Rate Injection Test

- Inject water at a number of flow rates while monitoring downhole pressures
- Plot pressure at the end of each step vs flow rate
- Normally get straight line and slope provides measure of overall well “Injectivity Index”
  - May get changes in slope if fracture pressure is exceeded or if shallow zones start accepting at high flow rates
Multi-Rate Injection Test, Bar-08RD (Tiwi)
Multi-Rate Injection Test, Bar-08RD (Tiwi)
Thermal and Multiple Zone Effects on Injectivity Test

- Under injection, pressure gradient initially changes due to lower temperatures

- **Injecting at W₁;**
  - Zone 1, $P_{wb1} < P_{res}$ inflow
  - Zone 2, $P_{wb1} > P_{res}$ outflow of all injected water + inflow from Zone 1
  - Fluid flowing in at Zone 1 is likely to be hot, which will cause density changes and affect the pressure measurements

- **Injecting at W₂;**
  - Zone 1, $P_{wb1} > P_{res}$ partial outflow of injected water
  - Zone 2, $P_{wb1} > P_{res}$ partial outflow of injected water
Thermal and Multiple Zone Effects on Injectivity Test

- Acuña (1994) describes a technique for correcting the measured pressure data when two zones are present, with inflow and outflow occurring at the upper zone and the associated thermal effects.
- To use the method, both temperature and pressure data need to be measured during the injectivity and pressure falloff tests.
  - Now commonly available due to use of PTS tool.
- Care still needs to be taken to check the quality of the data before applying these corrections.
Pressure Transient Analysis

- Pressure changes measured during the multi-rate injection test and after injection stops can be analyzed to provide additional information on overall reservoir properties and well conditions
  - Permeability-thickness (kh) or transmissivity
  - Presence of fractures
  - Outer boundary conditions (???)
  - Well “skin” factor
    - Near wellbore damage (positive)
    - Presence of fractures (negative)
  - Wellbore storage effects
Pressure Falloff Test, Bul-104 (Mak-Ban)

Bul-104 Diagnostic Plot

- Storage and skin model
  - Homogeneous
  - Infinite-acting

- Storage, STB/psi: 0.7165
- Skin: -3.604 ± 0.091
- Permeability-thickness, md-ft: 66170 ± 2.6%
- Initial Pressure, psia: 1895 ± 1.5
Multi-Rate Analysis, Bul-104 (Mak-Ban)

- Not always possible to get a good match to all the steps in the multi-rate analysis
- Generally see improvement during injection

1. $P_2 < P_1$ at the same injection rate
   Indicates that well injectivity was improving

2. measured calculated
Shut-in Surveys During Well Heat-Up
Shut-in Pressure / Temperature Surveys

- After the well is completed, downhole surveys are run to monitor temperature and pressure changes while well is heating up

- Data provide information on:
  - Permeable zone locations
  - Thermodynamic conditions at the feedzones and in the wellbore (steam, gas, two-phase or water)
  - Presence of flow in the wellbore (up or down)

- And on reservoir conditions:
  - Temperature inversion, indicating outflow
  - Conductive gradient, indicating low permeability
  - Convective gradient, indicating reservoir conditions
Island Arc Type Geothermal System
Shut-in Pressure Surveys

- As well heats up, pressure gradient changes due to decrease in fluid density
- Pressure profiles may then “pivot” around the “pressure control point”
  - Location dependent on relative permeabilities of the zones in the well and is the only point where measured pressures are not affected by temperature changes
Typical Pressure Gradients

- Water gradient depends on temperature.
- Two phase gradient depends on steam fraction.
- Steam or gas.
Saturation Curve for Water/Steam

- Temperature (°F)
- Pressure (psia)
- Compressed Water
- Superheated Steam

"Saturation curve"
Boiling-Point-Depth Curves

- **Temperature (°F)**
  - 0, 100, 200, 300, 400, 500, 600, 700, 800
- **Depth from water level (ft)**
  - 0, 1,000, 2,000, 3,000, 4,000, 5,000, 6,000, 7,000, 8,000, 9,000, 10,000, 11,000
- **Pressure (psia)**
  - 0, 500, 1,000, 1,500, 2,000, 2,500, 3,000, 3,500
- **Depth from water level (ft)**
  - 0, 1,000, 2,000, 3,000, 4,000, 5,000, 6,000, 7,000, 8,000, 9,000, 10,000, 11,000

**Compressed Water**

**“Saturation” two-phase curve**
Heat-Up Surveys from OW-911A and OW-912 (Olkaria, Kenya), Axelsson and Steingrímsson (2012)

On saturation
- steam or two-phase zone
Downhole Surveys, Nag-01 (Tiwi)

Temperature (degF)

Pressure (psig)

$T_{\text{meas}} < T_{\text{BPD}}$

= single phase water
Downhole Surveys, Nag-06 (Tiwi)

\[ T_{\text{meas}} = T_{\text{BPD}} \]

= two-phase or steam
Downhole Surveys, Nag-69 (Tiwi)

“conductive” gradient = low permeability
Typical Temperature Profile -1

What is this part of the reservoir like?

What are the fluid conditions like here?

….. and here?
What is this part of the reservoir like?

Why are these temperatures declining?
Typical Temperature Profile -3

What is this part of the reservoir like?

What are the fluid conditions like here?
Temperature / Pressure Surveys from Mak-Ban Deep Wells Affected by Cross Flow

Temperature (degF)

Pressure (psig)

\[ P_{wb} > P_{res}; \text{ outflow} \]

\[ P_{wb} < P_{res}; \text{ inflow} \]
Well Flow Testing
Well Flow Testing - Objectives

- When the well has heated sufficiently, it will be flow tested to obtain information on well productivity and fluid chemistry.
- The flow test equipment required will depend on the well completion (slim or full size), environmental requirements, etc.
- If the well cannot self flow, it may be necessary to use additional equipment to initiate flow.
- Initial flow test may be to a sump and may only last for a few hours / days if the discharge water cannot be disposed of.
  - May need to inject back into the well from the sump.
- Longer term flow tests may require drilling of a second well so discharged water can be injected.
Well Flow Testing - Objectives

- Measure total mass flow and discharge enthalpy at various wellhead pressures and as function of time
  - Steam and brine flows at specified pressures
- Gas (NCG) and fluid chemistry
- Downhole thermodynamic conditions from flowing PT and/or PTS surveys
  - Are the feed zones single phase water, two phase or single phase steam?
  - Are there cool inflows?
  - Where is flashing (boiling) occurring? in the well or reservoir?
  - Is superheating occurring?
Well Flow Testing - Objectives

- Measured data will help determine plant design and operating parameters
  - Pipeline sizing
  - Optimum separation/inlet pressures
  - Gas processing capacity
  - Corrosion/scaling mitigation requirements
- Determine production and injection well requirements
- Provide information on reservoir conditions to incorporate in conceptual and numerical modeling
Initiating Well Flow

- This may be an issue in exploration, particularly at higher elevations where liquid levels can be expected to be deep in the well.
- Required when wells are unable to flow spontaneously because:
  - Downhole temperatures are well below boiling-point-depth (BPD) curve - need to lift off significant water before flashing will occur.
  - Low temperatures near surface which will cause heat loss as fluid flows up the well.
  - No build-up in wellhead pressure even though well is hot.
Initiating Well Flow

- Methods used are designed to remove or lighten the water column to allow boiling to occur and the well to flow or to heat up shallow casing.

- Common methods include:
  - Airlifting/Nitrogen injection using coiled tubing
  - Compression using air compressor
  - Steam or two-phase injection from package boiler or nearby well
  - Others (swabbing, etc)
Air or Nitrogen Lifting

- Tubing is installed to a depth approximately twice the depth to the water level
- Air or nitrogen is injected through the coiled tubing to aerate the liquid column
- The liquid rises up the well and is eventually discharged
- As the flow to surface is initiated, deeper, hotter liquid is produced and a flashing two phase discharge becomes established and the tubing is then stripped out of the well
Well Flow Testing - Techniques

- Measurement of flow is difficult due to the nature of two phase steam/water flow
- Number of techniques now considered standard in the geothermal industry:
  - *James “lip pressure” method*
  - Separator
  - Chemical tracer techniques
  - “Other” techniques
    - Variations on James Method – Japan, Russia
    - Two phase orifice plates
James “Lip Pressure” Method

- Based on experiments undertaken by Russell James in Wairakei, New Zealand, involving critical flow of steam water mixtures to the atmosphere
- From the experimental data, an equation relating “lip” pressure measured at the end of a discharge pipe to enthalpy and massflow was developed

\[ w_{tp} = \frac{C \cdot A \cdot p^{0.96}}{h_{t}^{1.102}} \]
James “Lip Pressure” Method

- To solve for both enthalpy and massflow, require second relationship which is then solved simultaneously with the James equation

- Can use:
  - Weirbox to measure separated water flow
    - relationship to total flow and enthalpy based on mass and energy balance at atmospheric pressure
  - Orifice to measure total two-phase flow
    - relationship between orifice $\Delta p$, total flow and enthalpy based on relationship developed by James from experimental data

- Weirbox method considered to be more accurate than orifice method
James “Lip Pressure” Method

- Easy to construct and set up in remote locations
- Provides total flow and enthalpy data with satisfactory accuracy
- Can be instrumented to provide continuous data
James “Lip Pressure” Method

Tongonan
Philippines

Dixie Valley
USA

Las Tres Virgenes
Mexico
Flow Test Example – 15 Days Duration

- Well flowed at 3 different WHP conditions
- Total flow and enthalpy measured using “James” method
- Steam/brine flows calculated at 10 bar.a and power capacity based on plant steam usage of 7 t/hr/MW
Deliverability Curve Example

- Flow and enthalpy data plotted vs Wellhead Pressure to define the Deliverability Characteristics
- Indicates that well can provide max initial steam flow of 33 t/hr; equivalent to a Power Capacity of 4.7MW
Flowing Surveys (PT or PTS)

- Flowing surveys are run to provide information on:
  - Location of permeable zones
  - Relative production from each zone (PTS survey)
  - Thermodynamic conditions within the well
    - Where is flashing occurring; in the formation or the wellbore?
    - What are the thermodynamic conditions of the inflow fluids; two-phase, single phase water or steam?
  - Level of pressure drawdown and estimate of “Productivity Indexes” for the well and the individual zones
Thermodynamic Changes During Flow

**Compressed Water:**
- Temperature remains constant as pressure declines
- Pressure gradient is liquid

**Two-Phase:**
- Temperature is a function of pressure and declines as pressure declines
- Pressure gradient less than liquid and is a function of steam fraction

**Saturated or Superheated Steam:**
- Temperature on or above (if superheated) saturation
- Pressure gradient for dry steam
Typical Pressure Gradients

- Water gradient depends on temperature.
- Two phase gradient depends on steam fraction.
- Steam or gas
Flowing P/T Survey Example

- Simple example showing flow from a 250°C single phase liquid source, with flashing at 1,200m (VD)
- Pressure gradient changes from water to two phase and temperature starts to decline along with pressure above the flash point
Flowing PTS Analysis, Bul-112 (Mak-Ban)  
*Acuna and Arcedera, 2005; Regulacion, 2006*

- Enthalpy (orange) profile is calculated from the pressure profile, corrected for friction
- Massflow (black) profile is calculated from the enthalpy and fluid velocity profiles
- Change inflow parameters (massflow and enthalpy) until the best match is obtained to all the profiles

80 kph, 1200 BTU/lb  
90 kph, 275 BTU/lb  
125 kph, 275 BTU/lb  
100 kph, 600 BTU/lb  
50 kph, 600 BTU/lb  
50 kph, 550 BTU/lb

Cool inflows as shown by change in pressure gradient
Superheated Steam Well, Mat-23 (Tiwi)

Well encountered both deep liquid and shallow steam conditions

Flowing PTS indicates well only flows from steam zone and condition is superheated steam even though liquid level is only 300ft below production zone

Mat-23 has been a stable producer since mid 1990’s

**Under shut-in conditions**
- \( T_{\text{meas}} = T_{\text{satn}} \)

**Under flowing conditions**
- \( T_{\text{meas}} > T_{\text{satn}} \)
- \( T_{\text{SH}} = T_{\text{meas}} - T_{\text{satn}} \approx 55 \, \text{degF} \)

*Menzies et al. (2010)*
Pressure Buildup Test (PBU)

- The well pressure response to shutting in the well can be measured and it may be possible to analyze the data to provide additional information on overall reservoir properties and well conditions
  - Permeability-thickness (kh) or transmissivity
  - Presence of fractures
  - Outer boundary conditions (???)
  - Well “skin” factor
    - Near wellbore damage (positive)
    - Presence of fractures (negative)
  - Wellbore storage effects
Pressure Buildup Test (PBU)

- A pressure tool is run downhole to the desired measuring depth prior to shutting in the well, if possible, or as quickly as possible after the well is shut-in
  - If well produced dry or superheated steam, the wellhead pressure can be monitored instead
- Best results are obtained if the well produced from single phase liquid or steam zones as the fluid properties are then known
- If two-phase conditions are present, the fluid compressibility, viscosity, etc need to be corrected to in-situ conditions and this may not be well understood so results will be less definitive
- If there are wellbore effects, such as crossflow, where flow continues from one zone to another after shut-in, then it is unlikely that the data will provide useful information on reservoir properties
Response is well behaved and estimated transmissivity, based on the measured slope, is 4 D.m, which is high.

Instrument was not run in prior to shut-in so initial pressure was not obtained – cannot estimate “skin” factor.
Pressure Buildup Test, Well 401, Tongonan
Menzies (1979)

- Response initially well behaved but starts to cycle after 3 hours due to crossflow in the wellbore
- Based on initial response, estimated transmissivity is 4.5 D.m
- Initial shape suggests wellbore storage / skin type response
Multiple Well Flow Test
Multiple Well Flow Test - Objectives

- Once sufficient wells are drilled, a multiple well flow test may be run to measure the impact of additional production on the reservoir
- The test is normally conducted for 1 to 6 months
- During the test, production parameters from all wells are monitored to determine how the mass flow and enthalpy are changing with time
- Reservoir pressures are also monitored in observation wells (if available) to monitor how the reservoir responds to production and/or injection
- A tracer test may also be conducted to check on communication between injection and production wells
Multiple Well Flow Test - Objectives

- The pressure responses are analyzed to determine average reservoir flow capacity (transmissivity) and storage capacity (storativity)
  - Qualitative analysis is also important - which wells are affecting the observation well(s) and how much impact are they having
  - Results can be used to calibrate an analytical model of the field that can be used to forecast field behavior if the reservoir produces single phase liquid or steam

- The changes in production parameters and the measured pressure data can also be used to calibrate a reservoir simulation model to provide the ability to do initial forecast runs
  - Has more flexibility than an analytical model and can be used if two-phase conditions are present
Pressure Monitoring Equipment

- Due to the high downhole temperatures, there are limited equipment options for long term downhole pressure monitoring.
- Best option is to use capillary tubing in the well connected to a transducer/datalogger at the surface:
  - The capillary tubing and chamber are run into the well to desired depth
  - System is purged with inert gas (helium or nitrogen)
- These systems are used in many geothermal fields for long term pressure monitoring.
Capillary Tubing Installation
Multiple Well Test; Zunil, Guatemala

Menzies (1990)

- Test conducted from March to November 1989 and involved all six ZCQ-wells as production and/or observation wells.
- The test provided information on the resource that was later used to justify a 24MW development that started operations in 1999.
Multiple Well Test; Zunil, Guatemala

Menzies (1990)
Numerical Model, Zunil Geothermal Field
Matches Using Numerical Model

[Graphs showing pressure changes over time for ZCQ-8, ZCQ-1, and ZCQ-4.]
“Six Well” Flow Test, Dixie Valley, Nevada

*Desormier (1987)*

- Extensive test that was carried out from July to Oct, 1988
  - 6 production wells
  - 7 observation wells
- Test was conducted to determine that adequate resources existed for the planned 66MW development
- Test results were an important component in obtaining the necessary financing and in determining future make-up well requirements
- Plant has been on-line since 1988 and has maintained very high capacity factors
Cross Section, Dixie Valley

Reservoir Temp: 220 - 250°C at 2.3 - 3.0 km

Direction of Hot Water Movement

3 km in 10 Ma

NW

SE

Triassic Shale

Alluvium

Permeability Barrier

Miocene Basalt

Triassic Sedimentary and Volcanic Rocks

Gabbro and Anorthosite (Humboldt Lopolith)

Triassic Shale

Granite

STILLWATER FAULT

H L

52°
“Six Well” Flow Test, Dixie Valley, Nevada

Desormier (1987)
“Six Well” Flow Test, Dixie Valley, Nevada

Match to Observation Well Response
References

References

End of Presentation

Thank you