Best Practices in Geothermal Operations and Maintenance

Reservoir Monitoring & Management

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Introduction

1. Changes in Power Plant Supply or Injection Capacity related to Changes in Reservoir Conditions
2. Reservoir management tools
3. Reservoir changes affecting operations: causes, observations, resulting changes in resource supply and injection capacity
4. Monitoring: Data Collection
   1. Without interrupting operations
      1. mass flow, enthalpy, reservoir P, chemistry, well P, T+ special testing (eg tracer testing, caliper logs etc)
   2. Special testing
5. Interpretation tools
6. Examples:
   1. Cooling: injectate or groundwater breakthrough?
   2. Boiling and change in enthalpy: near wellbore vs reservoir wide boiling
   3. Injection declines: reservoir pressure vs mineral saturation
Objective

Why manage the reservoir?
To maintain mass flow, enthalpy and chemistry of geothermal fluid supply to the plant and injection capacity for plant discharge
To manage we need to monitor reservoir conditions as manifested in wells.
Changes in Power Plant Supply or Injection Capacity related to Reservoir Conditions

• Cooling and enthalpy decline of production fluids, changing brine/steam ratio and increasing injection
• Production enthalpy increase changing brine/steam ratio
• Production decline in mass flow
• Injection decline in capacity or pressure increase,
• Chemical changes (including noncondensible gas (NCG), scaling)
Reservoir Management Tools

• Tools are limited
• Changing flow rates of individual wells: no cost but restricted by power plant supply requirements (production) and discharge requirements (injection)
• Change production and injection wells: needs gathering system change
• Well maintenance: mechanical or acid clean outs, stimulation, work overs
• New well drilling: $3-10,000,000
• Plant modifications: increase gas extraction capacity, lower inlet pressure, scale mitigation

The better the problem can be framed, the less risk in the solution
Effects of Exploitation on Reservoir Conditions and Subsequently on Production and Injection Capacity

- High withdrawal rates without sufficient injection support or interference $\rightarrow$ pressure decline $\rightarrow$ boiling $\rightarrow$ a vapor phase in liquid reservoirs and/or lowering liquid saturation in vapor reservoir $\rightarrow$ scaling, differential vapor/liquid flow from the well, “excess enthalpy”, change in NCG

- High withdrawal rates without sufficient injection support/interference $\rightarrow$ pressure decline $\rightarrow$ groundwater or injection influx (breakthrough before heating) $\rightarrow$ cooling

- Over injection in one place or interference between injection wells $\rightarrow$ local reservoir pressure increases $\rightarrow$ high injection pressure $\rightarrow$ more pump capacity or lower injection rates

- Changes in reservoir pressure ($P$) temperature ($T$) $\rightarrow$ fluid no longer in equilibrium with rocks $\rightarrow$ scaling

- Reservoir compartmentalization with uneven permeability distribution (faults or stratigraphy) and uneven injection and/or production $\rightarrow$ reduced or uneven benefit of injection support or uneven recharge

- Continued reservoir boiling $\rightarrow$ “dry” reservoir rock $\rightarrow$ superheated steam $\rightarrow$ volatile Cl corrosion

- Power conversion cycle effects the reservoir changes and the monitoring parameters, if the fluid doesn’t boil, injection looks like productions
Reservoir Monitoring Program

• Collecting data to monitor reservoir processes and anticipate problems that might adversely affect the resource supply or injection capacity

• Reservoir monitoring under normal operations without affecting well production or injection
  • Production wells: mass flow, WHP, WHT, enthalpy (H), 2-phase (2\(\phi\)) or single-phase (1\(\phi\)) chemistry
    • How do you measure flow/enthalpy if you have 2\(\phi\) and centralized separation?
    • Tracer testing: on line testing for pumped and flashed systems
  • Injection wells: mass flow, WHP, WHT, chemistry
  • Observation wells: reservoir pressure, depth
  • Power Plant/Control System data: weighted average from wells at power plant inlet

• Special testing (eg. PTS surveys, interference testing, caliper logs etc)
Invest in equipment
Reservoir Monitoring Data Management and Interpretation

- Integrated Database
  - QA/QC data
  - Cross check well data with Plant data
- Temporal Trends
  - BASELINE CONDITIONS!!!
- Parameter Comparison
- Geochemical evaluation (e.g. liquid saturation, geothermometers, multicomponent trends)
- Wellbore simulations
- Reservoir conceptual and numerical modeling
Reservoir Data

Control system data
Daily observations
Periodic Data
Weekly Data
Initial Conditions
Well AZ-13 Los Azufres

Wellhead pressure (WHP), 40 bar (partial shut-in) to 10 bar increased to 20 bar

Total mass flow drops, but steam increases liquid decreases

Bottomhole (BHP) pressure slight drop

Bottomhole enthalpy significant increase to slight superheat

Enthalpies, (H) Measured (↑), silica (↓) and Na/K (-) geothermometers

(When $H_{\text{meas}} > H_{\text{NaKCa}} > H_{\text{qtz}}$, near wellbore boiling has produced excess enthalpy and higher measured enthalpy as well as cooling the fast acting quartz geothermometer, but the Na-K-Ca geothermometer still reflects the enthalpy of reservoir liquid.)

Chloride (Cl) decreases in both separated water and total discharge-water is condensate, brine disappears

WHAT’S GOING ON HERE?

Initial Production at full flow, 2φ, 260°C, dropped WHP, BH pressure dropped below saturation and boiling occurred.

Steam flow stabilized after 1998 at 80 tph at 20 bar.

Additional local boiling cooling near wellbore

Note that at initial conditions of 1100 kJ/kg and 120 tph, probably only produced about 25 tph of steam, so if the plant is a flash plant, more steam is provided after boiling,
Example #1 Pressure Decline leads to Cooling of Produced Fluid and Boiling

• Injectate or groundwater breakthrough?
• Why does the reservoir manager care?
  • Groundwater → more injection
  • Injectate → less injection
• Monitoring data-key parameters depend on system:
  • WH enthalpy (or temperature if 1φ) to confirm cooling wells
  • SiO2 to confirm cooling
  • Cl liquid dominated or 2 φ reservoirs,
  • NCG,
  • stable isotopes
  • Mg
Example #1-Wairaki
Initial conditions 250-260⁰C liquid-dominated, no injection until 1998

- 25km² area high horizontal permeability
- Initial production in the Eastern and Western Wellfields
- After initial 25 bar pressure decline, shallow steam zone developed and
- 30-50 ⁰C temperature decline mostly in shallow Eastern Wells 20 <200
Example #1-Wairaki

- Temperature declines in production area to 200⁰C
- CO₂ decreases and pH increases due to aquifer boiling
- Normally aquifer boiling would increase Cl, but in this case, Cl decreases
- Low Cl, low gas, groundwater influx
- Injection increases pressure
Example #1 - Wairaki

- Injection increases deep pressure, stabilizing after
- Flow maintained at 1030 kJ/kg by drilling make-up wells after 1980
- Enthalpy maintained by drilling shallow 500-600m steam wells in “high” pressure steam area
Binary Systems

• Pressure decline lowers the depth of boiling and/or draws in cold water and cools

• Flashed Binary-effects similar to flash systems
  • lower pressure effects the depth of boiling and scale inhibitor systems
  • Cooling changes the proportions of liquid and vapor

• Pumped Binary-
  • chemistry doesn’t change through plant except as related to cooling so Cl is not an indicator of injectate
  • Cooling raises and boiling can lowers the required pump depths
Enough?
Example #2 Reservoir Boiling and Excess Steam

• Discussed above in Los Azufres
• Increases enthalpy of produced fluid by increasing steam/brine ratio
• Increases pressure drop and actually cools reservoir
• Noncondensible gas in total flow typically increases as the steam increases,
• Geothermometers (liquid and gas) and near wellbore vs reservoir wide boiling
Cooling and MW Decline in MW at Blue Mt- Injection breakthrough

Figure 19: Blue Mountain historic performance data. Red line documents the plant inlet temperature over time, reflecting the injection/production strategies operators took over time in order to mitigate thermal decline. Current thermal decline is 30% of its initial rate. Blue line displays the gross power generation over time. Generation has been mostly stable since 2015 due to a series of field and plant optimizations performed.
Tracer Testing and modeling confirmed temperature decline related to injection.
Thank you!
Well AZ-18 Los Azufres

Total mass flow erratic then declines, but steam flow stabilizes liquid decreases

Bottomhole (BHP) pressure stable

Bottomhole enthalpy significant increase to slight superheat

Enthalpies, \( (H) \) Measured (↑), silica (-) and Na/K (-) geothermometers

When \( H_{\text{meas}} > H_{\text{NaKCa}} = H_{\text{qtz}} \), reservoir wide boiling substantial enough that both geothermometers equilibrate to changing liquid temperatures but the measured enthalpy reflects excess steam.

Chloride (Cl) increases separated water and decreases total discharge

NCG as CO2 increases to

WHAT’S GOING ON HERE?

Initial Production at full flow, 2φ, 260⁰ low rates.

Steam flow stabilized after 1998 at 80 tph at 20 bar.

Note that at initial conditions of 1100 kJ/kg probably only produced about 25% steam, after boiling, 50% steam increasing to 100%, but the total flow increases, so the vapor phase flows more readily

Constant reservoir temperatures (from geothermometers) suggest the boiling is reservoir wide not local
Different types of “Excess Steam”

Figure 11. Relation between Cl and discharge enthalpy. A: Excess enthalpy is due to conductive heat transfer from aquifer rock to fluid flowing into well (closed system). B: Excess enthalpy is caused by phase segregation in the producing aquifer (open system).
Using gas chemistry to monitor the reservoir boiling and saturation
Once a well stops producing liquid, there is only P, T, flow and gas and isotope chemistry

Steam fractions (y-values) and geothermometers in wells completed in steam, 2-phase and liquid-dominated sections of the same reservoir