PRODUCTION, INJECTION AND CLOSED-LOOP TESTING AT HABANERO EGS PROJECT

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ABSTRACT

Geodynamics Limited (GDY) has been developing an Enhanced Geothermal System (EGS) in hot granites beneath the Cooper Basin, Australia, since 2002. Four wells have been drilled at the Habanero site to depths exceeding 4,200 m and all four wells have penetrated a major fault which forms the reservoir. The temperature in the reservoir has been measured at 244°C at ~4,220 m below the surface.

In November 2012, the latest well, Habanero 4, was stimulated and production tested. The stimulation was done with water and injection rates of up to 53 kg/s were achieved. Following this stimulation, a maximum production flow rate of 39 kg/s was achieved in open flow mode.

Commencing in April 2013, Habanero 4 and Habanero 1 were operated in closed-loop mode, with Habanero 4 as the producer and Habanero 1 as the injector. Circulation was established and maintained with the aid of a surface pump, re-injecting the produced geothermal brine back into the reservoir. The heat produced was used to power a 1 MWe pilot power station.

The results of these production, injection and closed-loop tests will be discussed and compared to earlier tests conducted at Habanero. Combining the results of production, injection and closed–loop tests, the likely performance of future wells at Habanero will be discussed.

1. BACKGROUND

1.1 Location

The Habanero EGS project is located near the town of Innamincka in South Australia (Figure 1), approximately 900 km NNE of Adelaide.

1.2 Drilling History

The presence of hot granite at Habanero was first established when it was penetrated by a petroleum exploration well, McLeod 1, in 1983 (Figure 2) and a temperature of 199°C was recorded within the granite.

GDY drilled its first EGS well, Habanero 1 (H01), in 2003, penetrating the granite at 3,667 mRT. H01 encountered a permeable fracture system in the granite, containing over-pressured brine. After weighting up the drilling mud to balance the over-pressure, approx 250 m^3 (1,600 bbl) of heavy weight mud were lost into the fracture system before bringing the well under control. The well was completed with a 6 inch open hole section in the granite and 4½ inch tubing. The well was stimulated in 2003 (Table 1) and this stimulation created a cloud of micro-seismic events over an area of 2.9 km^2. All subsequent wells have penetrated that seismic cloud.

Habanero 2 (H02) was drilled in 2004 but encountered drilling problems resulting in a sidetrack around a "fish" in the original hole. During completion of the 6 inch sidetrack, a bridge plug was lost down hole and became stuck in open hole just above the main fracture zone. Although the well was stimulated and tested, these tests were all affected by the presence of the bridge plug.

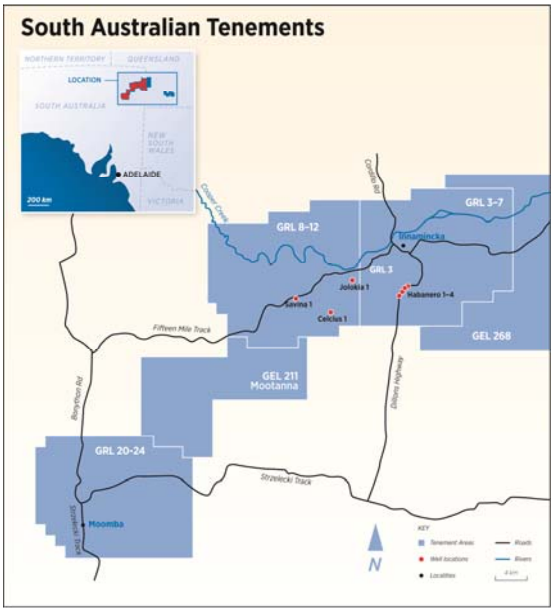

Figure 1: Location of Habanero EGS Project, approx 900 km NNE of Adelaide.

Habanero 3 (H03) was drilled in 2008 and successfully completed with a pre-drilled liner hung across an 8 ½ inch open hole granite section and a short 7 inch kill string.

Habanero 4 (H04) was drilled in 2012 and completed with an 8 ½ inch open hole granite section and 7 inch tubing.

Figure 2: Satellite view of Habanero, showing locations of wells and surface equipment.

1.3 Reservoir Description

Acoustic borehole images and production logs show that the majority of flow into or out of the granite occurs over a relatively thin zone of intense fracturing. This zone is approx. 5 m thick and, based upon the seismicity caused by stimulation (McMahon and Baisch, 2013), is interpreted to be a shallow dipping, thrust fault known as the “Habanero Fault”.

1.4 Static Conditions

An arbitrary reservoir datum depth has been established at 4,140 mSS, approximately the depth of the Habanero Fault half-way between H03 and H01. Static bottom hole conditions at this datum have been estimated from pressure build-up tests conducted in H03. The static datum conditions are 244°C and 73 MPa.

Static surface conditions have been measured with a production log recorded in H01 in 2005 after 18 months shut-in. The static surface pressure is 33.7 MPa with water in the well.

2. PRODUCTION TESTS

Production tests have been conducted on three Habanero wells: H02, H03 and H04. As noted earlier, the tests on H02 are affected by the presence of a bridge plug stuck in the open hole so these results are not considered valid.

All these production tests have been conducted with relatively short, constant mass rate flow periods. Stable flowing conditions were rarely reached for any of these tests because of the limited volume of the reservoir and the temperature transients affecting fluid density in the well bore. The data used in all plots have been taken from the end of each constant rate period, when the pressure, rate and temperature are at their most stable.

2.1 Bottom Hole Productivity

Production logs have been recorded during five production tests so far at Habanero (Figure 3). All down hole pressure data has been corrected to the datum depth assuming a column of brine in the well.

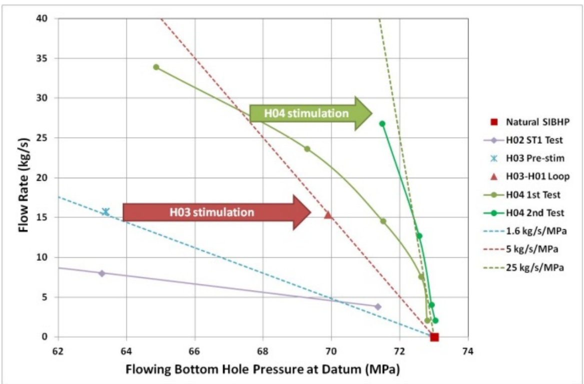

Figure 3: Production flow rate versus flowing bottom hole pressure, showing stimulation effects.

Two single-rate production tests were done at H03: one before stimulation; and the second after a relatively small “local” stimulation, recorded at the end of the H03-H01 closed-loop (refer Table 1 and Section 4.1). Comparison of the flowing pressures from these two tests (Figure 3) shows a three-fold increase in bottom hole productivity from 1.6 to 5 kg/s/MPa after the stimulation.

Three multi-rate tests were done at H04, though only the first and second were run with down hole gauges. The first multi-rate test, done before stimulation, showed very high productivity at low rates, but a distinct reduction of productivity at higher rates. This result suggested that some turbulent flow was occurring near the well bore, especially at higher flow rates.

The second multi-rate test, done after local stimulation (Table 1), showed a significant increase in productivity at higher flow rates, with an almost linear response at ~25 kg/s/MPa, suggesting that turbulent effects are minimal within the range of test rates. This test also confirmed the finding from H03 that relatively small, local stimulations are effective for reducing near well bore impedance.

2.2 Surface Productivity

Surface production data at Habanero (Figure 4) show the form of productivity relationship typical of geothermal wells. Production at relatively low rates is at flowing well head pressures greater than the natural shut-in well head pressure (SIWHP). This is because the relatively cooler and heavier brine in the shut-in well is replaced with hotter and lighter brine during production.

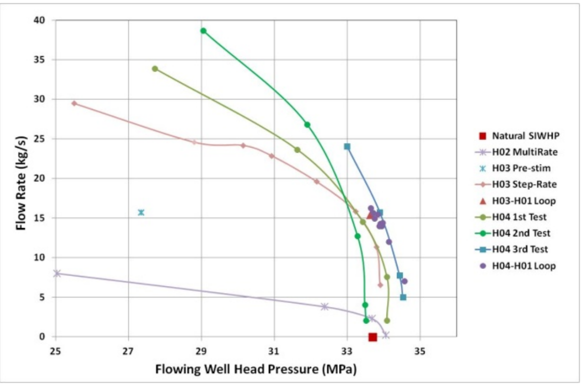

Figure 4: Production flow rate versus flowing surface pressure.

The first reliable production test was a step-rate test done at H03 after completion of closed-loop testing in 2009. The results (Figure 4) show a distinctly curved trend, suggestive of turbulent effects somewhere in the system. A maximum rate of 29 kg/s was achieved.

The first multi-rate test at H04, done before stimulation, shows improved productivity in comparison to H03, though again with some evidence of turbulent flow. The second and third multi-rate tests demonstrate clearly the benefits of stimulation, with reduced turbulent effects and productivity improving markedly after both stimulations.

The second test concluded with a high rate period where a maximum rate of 39 kg/s was recorded (Figure 5). From the limited drawdown at this high rate, it is clear that higher rates could have been achieved, but the test was constrained by the flow metering capability.

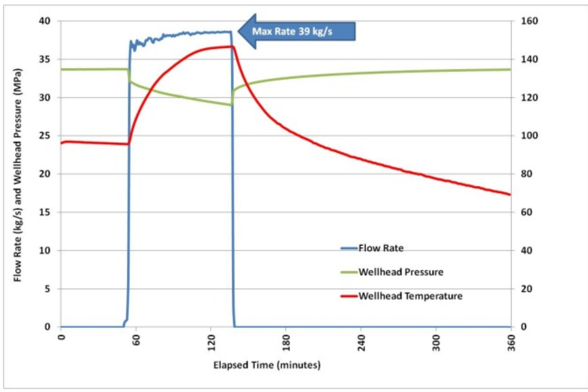

Figure 5: Maximum flow rate recorded from H04, 39 kg/s with limited drawdown.

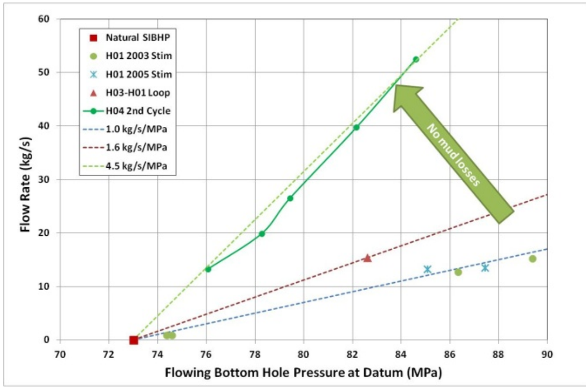

Figure 6: Injection rate versus flowing bottom hole pressure at datum.

3. INJECTION TESTS

Hydraulic stimulations have been conducted in all four Habanero wells. These hydraulic stimulations have by-and-large been done with fresh water without additives, though some NaCl saturated brines were used during early stimulation of H01. A summary of all the Habanero stimulation volumes is provided in Table 1 below.

Table 1: Stimulation history and volumes.

Stimulation	Date	Volume (ML)
H01 (2003)	Nov-Dec 2003	20
H02 (2005)	Jul-Aug 2005	3.8
H01 (2005)	Aug-Sep 2005	17
H03 (Local)	Apr 2008	2.2
H04 (Local)	Oct 2012	2.5
H04 (Extended)	Nov 2012	34

3.1 Bottom Hole Injectivity

Production logs have been recorded during three of the stimulations performed so far (Figure 6). Data from the two major stimulations of H01 show bottom hole injectivity of only ~1 kg/s/MPa, despite the large volumes of water injected during stimulation. As mentioned earlier, during drilling of H01 a large volume of heavy weight mud was lost into the Habanero Fault and this is believed to have created a damaged zone around the well where the fault is likely to be partially blocked with barite.

By the end of the H03-H01 closed-loop test (refer Section 4.1) bottom hole injectivity in H01 is estimated to have improved to ~1.6 kg/s/MPa, though no down hole gauges were run.

Bottom hole injectivity at H04 was ~4.5 kg/s/MPa during the local stimulation, which is a significant improvement in injectivity. Note that the bottom hole injectivity of both wells (H01 and H04) is more or less linear, showing no impact of turbulence which might be expected to occur near the well bore, especially at higher rates.

3.2 Surface Injectivity

The surface data from the Habanero stimulations (Figure 7) shows clearly how poor the injectivity is at H01. Despite having injected approx 33 ML of stimulation water, injectivity remained at around 1 kg/s/MPa.

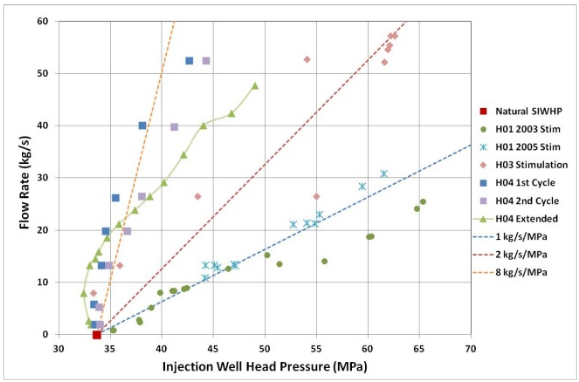

Figure 7: Injection rate versus injection well head pressure for all Habanero stimulations.

However, injectivity at H03 was significantly better, averaging around 2 kg/s/MPa at high injection rates and better still at lower rates.

H04 was stimulated twice: once with a small volume, local stimulation and then with a large volume, extended stimulation. The well achieved very high injectivities of 8-16 kg/s/MPa. For the final, extended stimulation, it is notable that a temperature-density effect is evident, with low rate injection occurring at pressures below the static shut-in pressure because the well has been filled with cold, dense stimulation water.

4. CLOSED-LOOP TESTS

A closed-loop test involves connecting two (or more) wells in a loop such that the total mass flow from the production well is re-injected into the injection well. There are no losses in the Habanero closed-loop: production mass rate is equal to injection mass rate. At Habanero, because of the high overpressure in the reservoir, the brine remains in single phase throughout the loop, without boiling or losing any of its dissolved gases. A brine re-injection pump on surface is used to re-pressurise the brine so that it can be re-injected.

Two closed-loop tests have been conducted at Habanero. The first was done in 2008/2009 using H03 as the producer and H01 as the injector. The second commenced in April 2013 using H04 as the producer and H01 as the injector.

4.1 H03-H01 Closed-Loop

The first closed-loop test was between H03 and H01, located 570 m apart. Over the period Dec 2008 to Feb 2009, a total of 61,000 tonnes of brine was circulated between the wells. Because of system constraints, the loop was operated within a narrow range of circulation rates from 13 to 15 kg/s. The maximum flowing temperature was 212°C and the maximum circulation rate achieved at the end of the test was 15.4 kg/s.

4.2 H04-H01 Closed-Loop

The current closed-loop test is between H04 and H01, located 690 m apart. Circulation commenced in April 2013 and, as of mid September 2013, a total of 150,000 tonnes of brine has been produced from H04. Most of this brine (89%) has been re-injected into H01 and the balance has been open flowed into storage dams. As of mid September, the flowing temperature is 213°C and the maximum circulation rate achieved is 18.9 kg/s.

4.3 Temperature Performance

Because the granite is deeply buried, there is ~4,200 m of borehole to heat in the production well and the same length of borehole to cool in the injection well. The impact of these long boreholes is a long, slow build-up of flowing temperatures over time, particularly at lower flow rates. Figure 8 shows the build-up of temperatures in H03 and H04 versus cumulative mass flow from the production well. Both tests show a continuing trend towards higher temperature even at the end of long periods of stable flow.

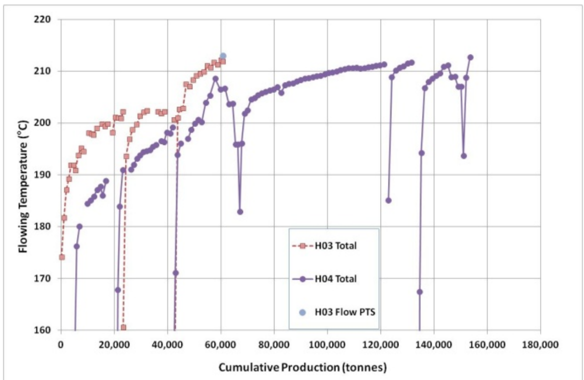

Figure 8: Flowing temperature versus cumulative mass production.

The lower temperatures at H04 are most probably a result of the recent stimulation which placed 36.5 ML of cool water into the Habanero Fault. This temperature drop has been recovered over time, but slowly. Fortunately, the slow build-up of wellbore temperature also means that wellbore temperatures drop slowly during shut-ins. The plot shows that temperatures return to trend quickly after shut-ins.

4.4 Loop Performance

Performance of the sub-surface portion of the closed-loop has been assessed by considering the pressure difference between the two well heads. Figure 9 presents a plot of closed-loop circulation rate versus that well head pressure differential.

The H04-H01 loop has been operated at a wide range of flow rates so that the performance relationship (or system curve) can be characterised. The loop has even been operated at very low rates where the well head pressure differential was close to zero. These tests have allowed determination of the thermosiphon effect (or buoyancy drive). For a test done early in the closed-loop trial (1st Step Test), the thermosiphon effect provided a flow rate of ~5.5 kg/s driven entirely by the density difference between hot and cold water.

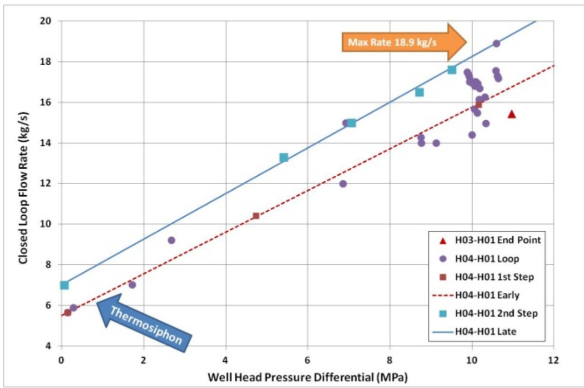

Figure 9: Closed-loop mass flow rate versus well head pressure differential.

Later in the closed-loop trial, a 2nd Step Test showed that the impedance within the reservoir had reduced (Figure 9) and that the thermosiphon effect was now driving a flow rate of ~ 7 kg/s.

Examination of the performance of both wells shows that the changes which are causing this improvement are occurring entirely at H01. One possible explanation is that this change may be a result of progressive dispersal of the mud solids blocking the fault as re-injection continues.

5. FORECAST LOOP PERFORMANCE

As has been shown from the closed-loop results achieved to date, the performance of a closed-loop depends not just upon the performance of an individual well, but upon the performance of the complete system i.e. the reservoir, the two wellbores and the surface pump. A convenient way to look at this is to combine the performance characteristics of the producer, the injector and the pump into one plot.

Figure 10 is a plot of the mass flow rates versus flowing well head pressure showing both H01 and H04 data in the current closed-loop. From this “Vee” plot it can be seen that the flow performance of H04 in closed-loop mode follows parallel to the post-stimulation production test results. However, flowing pressures are slightly higher than in open flow testing, most probably because of the pressure support from re-injection at H01.

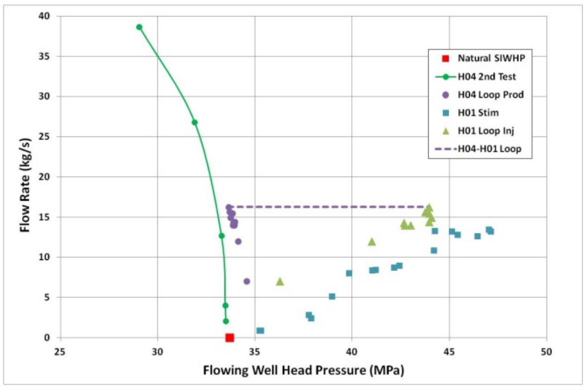

Figure 10: "Vee" chart showing closed-loop flow rates versus flowing well head pressures for H04 and H01. The "H04-H01 Loop" line shows the well head pressure differential as at end July 2013.

Similarly, the injection performance of H01 in closed-loop mode follows parallel to the stimulation injection performance. Again, the closed-loop injection pressures are slightly lower than during stimulation, most probably because of the pressure drawdown from production at H01.

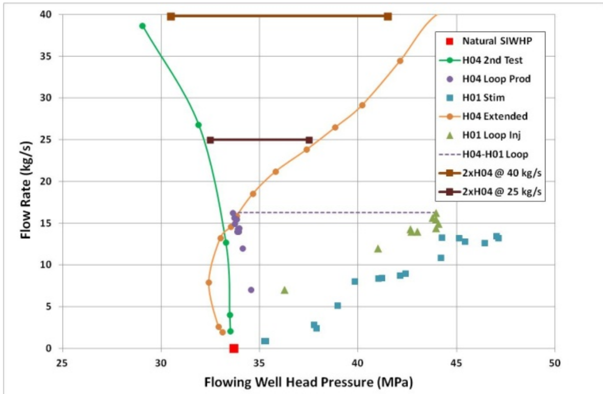

Figure 11: "Vee" chart showing potential closed-loop flow rates versus flowing well head pressures for two wells like H04.

If H01 was replaced by well with injection performance the same as that of H04, then significantly greater closed-loop flows could be achieved. Figure 11 shows the production test and stimulation performance curves for H04. With a well head pressure differential of 5 MPa, then closed-loop flow rates of ~25 kg/s could be achieved. Allowing a well head pressure differential of 11 MPa, then closed-loop flow rates of up to 40 kg/s could potentially be achieved.

6. CONCLUSIONS

The stimulation, open flow testing and closed-loop testing of Habanero wells have provided many lessons so far, of which the most important are:

- Near-well turbulent effects are evident before stimulation, but are greatly reduced or even absent following stimulation;
- Relatively small, local stimulation of wells drilled within the seismic cloud significantly increases injectivity and reduces near-well turbulent effects;
- Heat losses in long wellbores are significant and flowing well head temperatures increase only slowly;
- Continued circulation of the current Habanero closed-loop is delivering improvement in circulation rate;
- Closed-loop circulation rates are related to open-flow production test and stimulation performance and these data can be used to forecast potential flow rates;
- Future pairs of wells intersecting the Habanero fault should be able to deliver closed-loop rates between 25 and 40 kg/s.

REFERENCES

McMahon, A., and Baisch, S.: Case Study of the Seismicity associated with the stimulation of the Enhanced Geothermal System at Habanero, Australia. *Proc. 35th New Zealand Geothermal Workshop, Rotorua, New Zealand.* (2013).