

CHEMICAL REMOVAL OF FORMATION SCALE IN GEOTHERMAL PRODUCTION WELLS

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ABSTRACT

It is common for geothermal production wells to suffer from scaling while in operation, which can drastically decrease or halt production. The scale is usually calcite and can also contain silica which makes the scale harder and more difficult to remove. In reservoirs with significant silica in the fluids, the loss of production can be due to silica as much as calcite. In high enthalpy production wells flashing and scaling occur in the formation, and this is a much more difficult challenge than scaling in the wellbore, as formation scale can only be accessed with chemicals and not mechanical methods.

Traditional chemical methods of trying to recover such wells use hydrochloric acid (HCl), and whilst this impacts calcite, silica and silica-based deposits are not soluble in HCl. Some companies have tried using mud acid applied through a coil tubing unit. However, there are significant risks involved due to the strength and aggressiveness of the acids (corrosion, human and environmental risks), and results have been varied, so this approach has mostly been abandoned.

A partnership between Contact Energy, Solenis and Thermal Clean Ltd has developed and successfully applied new technologies to chemically clean formation scale in production wells using a combination of acid and caustic to remove both calcite and silica. This is the only viable method to recover production well formation scaling and has been successful in restoring dead production wells to 100% of maximum historical capacity. There are also indications the method could be a stimulation technique, dissolving formation minerals rather than just scale. Examples are given from New Zealand and Mexico.

1. INTRODUCTION

Recent collaborative efforts have led to the development and implementation of new methods to clean and stimulate geothermal production wells. This technique has been used to return non-producing production wells to 100% of their maximum historical capacity. This has been found to be the only viable method to reverse production well formation scaling.

Historically, coil tubing units (CTU) were used to spot feed hydrofluoric acid (HF) and/or mud acid (5% HF, 10% HCl) to the feed zone and found to be ineffective. Several challenges to this approach were studied, and some root causes of the variable results were identified. These causes are discussed in this paper.

A case study of the full recovery through acid/caustic chemical cleaning of a dead production well in New Zealand is also detailed.

2. BACKGROUND

2.1 Permeable feed zones in geothermal wells

Geothermal wells typically have long sections of the perforated liner (1 km or longer), where connections may exist between the wellbore and the reservoir if there is sufficient permeability at that depth (Zarrouk and McLean, 2019). “Feed zones” (also called “permeable feed zones”, or sometimes “loss zones” in the case of injection) in a geothermal well are depth intervals where sufficient permeability exists in the formation to allow flow into or out of the wellbore during production or injection. Formation scale forms at feed zone depths, extending out into the formation (Figure 1). There are no known methods of assessing the radial extent of the formation scale.

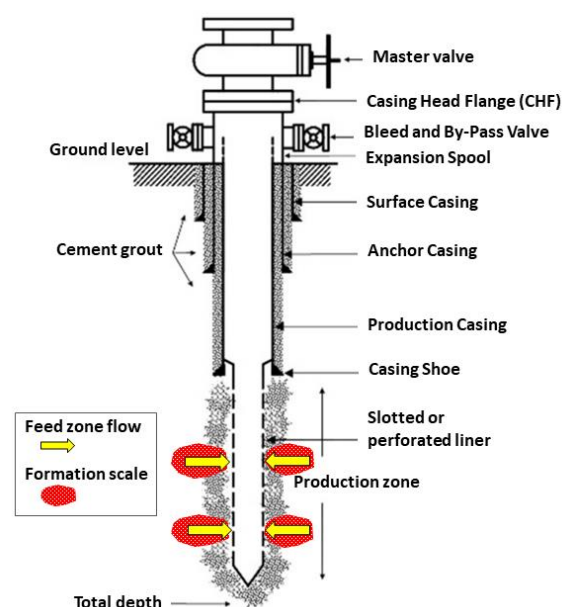


Figure 1: Schematic and terminology for a typical self-discharging geothermal well, showing permeable feed zones, flow during production, and location of formation scale (modified from Zarrouk and McLean, 2019).

Geothermal wells are rarely simple, with one feed zone. Wells usually have multiple feed zones, sometimes distributed over the length of the perforated liner, though often there is one feed zone that dominates the others (the “major feed zone”) (Zarrouk and McLean, 2019). The

permeability in feed zones can be an inherent feature from when the rock originally formed (primary permeability) or can be caused by fracturing/faulting (secondary permeability). At Wairakei Geothermal Field, feed zones frequently correlate with high-aperture fractures identified using borehole imaging (e.g., Massiot et al., 2015), which is secondary permeability.

2.2 Getting chemicals to where they are needed

For chemical cleaning of the formation to be successful, the chemicals must not only reach the permeable feed zones in the well, but once there, they must penetrate outwards the formation to react with the scale. In the past, chemical cleaning (with acid) has been performed by inserting a coil tubing unit into the well and “spotting” acid at target feed zone depths (Figure 2).

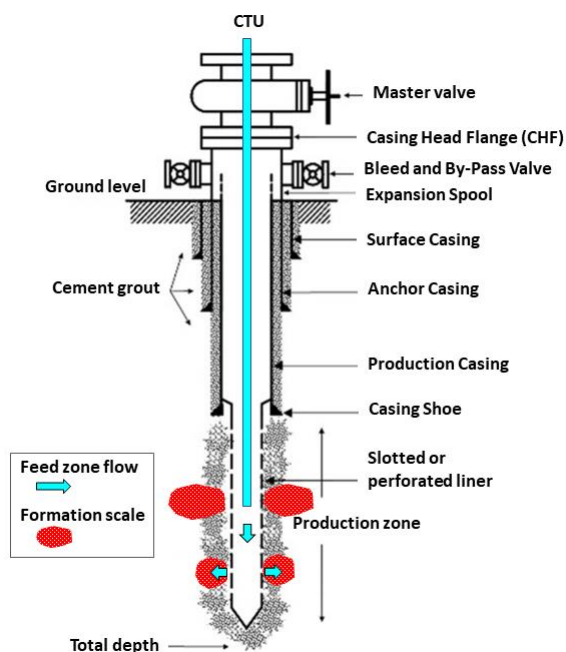


Figure 2: Schematic of CTU inserted into well, trying to spot acid to target upper feed zone but flow instead of taking the path of least resistance to the lower feed zone.

An issue with spotting chemicals with CTU that limits the effectiveness of this method is that the fluids being injected do not necessarily exit the wellbore into the formation at the base of the CTU. They travel up or down the wellbore, exiting into the formation via the path of least resistance. This may or may not be the location of the formation scale requiring treatment. Figure 2 illustrates an example of CTU trying to spot acid into an upper feed zone (which is blocked with the most scale and is the primary target), but instead, the fluid is moving down the wellbore and exiting at a lower feed zone.

Muller and Wilson (2019) studied online reinjection recoveries where the key to success was able to force fluid into as many permeable fissures in the formation as possible. The lower the pressure or volume of the flow that carries the cleaning chemistries into the formation, the fewer the fissures that will be cleaned because fluid, at any given pressure, follows the path of least resistance. The key, therefore, is to apply the chemistries at or above normal operating pressure and flow rates so that the higher pressures

will maximise the penetration of the scaled part of the formation (Figure 3).

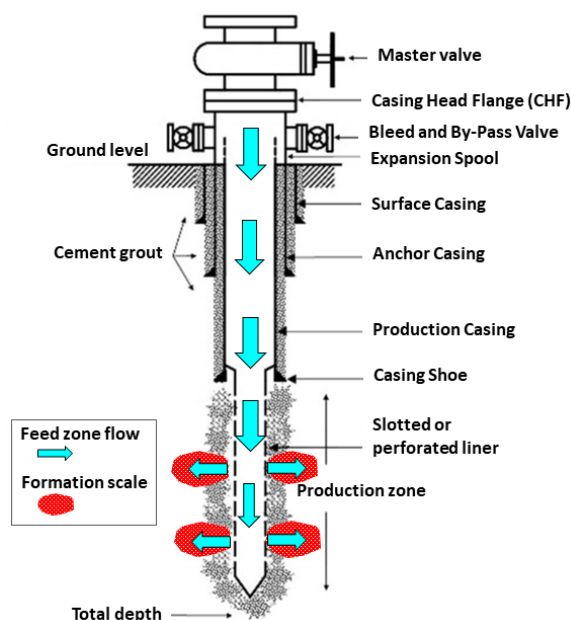


Figure 3: Schematic of “bull heading” fluid into a well from the surface, enabling high flow rates and maximising penetration of fluid into the scaled part of the formation.

Chemical cleaning using a CTU is less successful because the unit’s internal diameter and length limit pressures and flow rates. Typically, a 2-inch CTU that is 1000 m in length can deliver about 50 t/h. If the well can deliver 300 t/h, then the entire network of feed zones cannot be cleaned because the flow will follow the path of least resistance (likely the nearest feed zone) and will not reach all the feed zones.

This flow-pressure-reach relationship tends to imply that maximising the flow rate will create a better outcome; however, the flow rate is not the only consideration. The flow rate that delivers the maximum amount of chemical to the desired target feed zone may not necessarily be the highest flow rate, especially in multi-feed zone wells where the balance of feed zones changes between flow rates, as will be seen in the case study of WK260 below.

2.3 Changing fluid velocity profiles

As discussed in the previous section, the use of a CTU gives a false sense of assurance that the fluids are being delivered directly to the target feed zone. With a CTU in the well, it is not possible to run a PTS tool into the well to assess where the fluid is actually going. Injecting directly from the surface at full flow (bull heading) does permit a PTS tool to be run into the well. Sufficient spinner profiles (frequency vs depth) can be used to calculate a fluid velocity profile along the length of the well during injection.

If a well is operated at a constant flow rate, it develops a stable flow profile, with stable flow rates exiting at each feed zone. The magnitude of the flow depends on the permeability and thickness of the feed zone. In highly permeable wells (wells in which the pressure is fixed and pivots around a certain depth), fluid tends to exit at deeper feed zones as expected during injection, but also small inflows of reservoir

fluid occur at shallower feed zones (Zarrouk and McLean, 2019).

As injection rates change—and chemical cleaning changes the permeability—the magnitudes of the outflows/inflows of the feed zones change and sometimes even switch from inflow to outflow or vice versa. The balance between the different feed zones is too complex to predict and model; the only way to assess the balance is through downhole pressure-temperature-spinner (PTS) injection testing for different injection rates during the actual chemical cleaning job.

WK260 is an example where PTS studies identified the changing balance of feed zone flows, and the information was applied to optimise the effectiveness of the chemical clean (Section 4).

3. CHEMICAL CONCENTRATION AND SELECTION

Typically, standard acid jobs for production well clean use 15% HCl. The method described in this paper uses a combination of chemicals, including sequestrants, polymers, acids and alkali solutions. Key elements of the methodology include the pressure flow and control of the flow rates to the target zones that contain both carbonate- and silica-based deposits. Chemical brine analyses are used to determine the composition of the deposits and hence the relative proportions of the chemicals used in the steps in the cleaning process. However, a major differentiating component of this method, and another key component in reinjection well cleaning, is the use of targeted sequestrants for the types of cations that constitute the deposits in the formation.

Muller and Wilson (2019) documented the ability of different acids to remove metal silicates. By analysing the brine chemistries or, if possible, the deposits, it was determined which of the cations react with the silica in the formation to form deposits. Once these cations are dissolved from silicate deposits, they must be kept in solution to prevent redeposition elsewhere in the formation after the acid step is completed or after the formation neutralises the acid. Additionally, the dissolution of cations from the silicate deposits enhances the alkali step by increasing the porosity of the deposits.

It was also discovered that hydrophobic layers form on some silicates after they are exposed to acid. The effect of constantly flowing acid over these types of metal silicate deposits was very little, as documented by Rose et al. (2010). Thus, the method and oscillation of the chemicals become an integral part of the cleaning process. In the case of calcium carbonate deposits, the solution was more straightforward because HCl readily dissolves it.

Because much higher flows and pressures are used in the Solenis method than in traditional methods, a much lower chemical concentration is needed. The sequestrants and polymers are applied at the ppm level, the acids at less than 5% and the alkalis at approximately 2%.

A new development is the replacement of the typical corrosion inhibitors used in acidisation. Traditional inhibitors taken from the oil and gas industry are expensive and often use enhancers, such as antimony, that are poisonous and carcinogenic. Whilst it is not the topic of this

paper, an inhibitor from a food-grade base that is effective up to 200 °C has been developed. This new product makes the entire process, from a handling and environmental perspective, far safer.

4. CASE STUDY: PRODUCTION WELL WK260

4.1 WK260 Background

One of the most successful production well cleans carried out to date was at WK260, in the Te Mihi area of the Wairakei Geothermal Field in New Zealand. This 8 MW vertical well was drilled in 2009 to a total depth of 946 m (all depths in this paper refer to m below CHF, see Figure 1 for clarification of terminology), and cased to a depth of 463 m.

WK260 had been in decline since 2011, and by 2019 it had declined so much that it could not be returned to service after output testing, even though it could still produce a small output through a silencer. WK260 has multiple two-phase feed zones with flashing and a buildup of calcite and silica scale in the formation; hence it was selected as a candidate for chemical cleaning, as the scale was outside the wellbore and could not be accessed by any mechanical method.

The successful cleaning and stimulation of a production well in Mexico scaled with calcite and silica deposits has been previously reported (Rodriguez et al., 2020). However, the significant difference between the Mexican well and WK260 is the complexity of the feed zones. WK260 has multiple feed zones (nine, as described in Section 4.2) and several of those (the shallower zones) are inflows during the injection. The impact of inflows can be significant because the inflow can dilute any chemical that is bull-headed from the surface. Also, outflows shallower than the target feed zone divert some or all of the injection flow, potentially causing an insufficient quantity of cleaning chemicals to reach the target zone(s).

4.2 Identification of Feed Zones

During the WK260 clean, three full PTS injection tests were run: the first, prior to the cleaning job (Monday); the second, after the acid step (Wednesday); and the third, in the end, after the caustic step (Friday). The testing programs included three to four different injection rates (approximately 800, 1200, 1500 and 2000 lpm) to help assess the stable injection profile in the well at different flow rates. The program was kept as similar as possible for each test to allow results to be compared.

Figure 4 shows the fluid velocity profiles and the temperature profiles from the first PTS injection test on Monday, prior to any chemical cleaning. The interpreted feed zones are indicated by the shaded regions in Figure 4 and are summarised in Table 1. Table 1 also shows the magnitude of inflow/outflow at each feed zone. Inflows are indicated by increases in fluid velocity (and temperature), while outflows are indicated by decreases in fluid velocity (often with no significant temperature anomaly).

Figure 4 shows that, with sufficient injection rates, inflows can sometimes be suppressed and thereby become outflows. The shallowest feed zone (FZ1) is a significant inflow at the lowest injection rate of 795 lpm (blue line), but the inflow is then suppressed, becoming an outflow at an injection rate of 1199 lpm (green line). However, the highest injection rate is

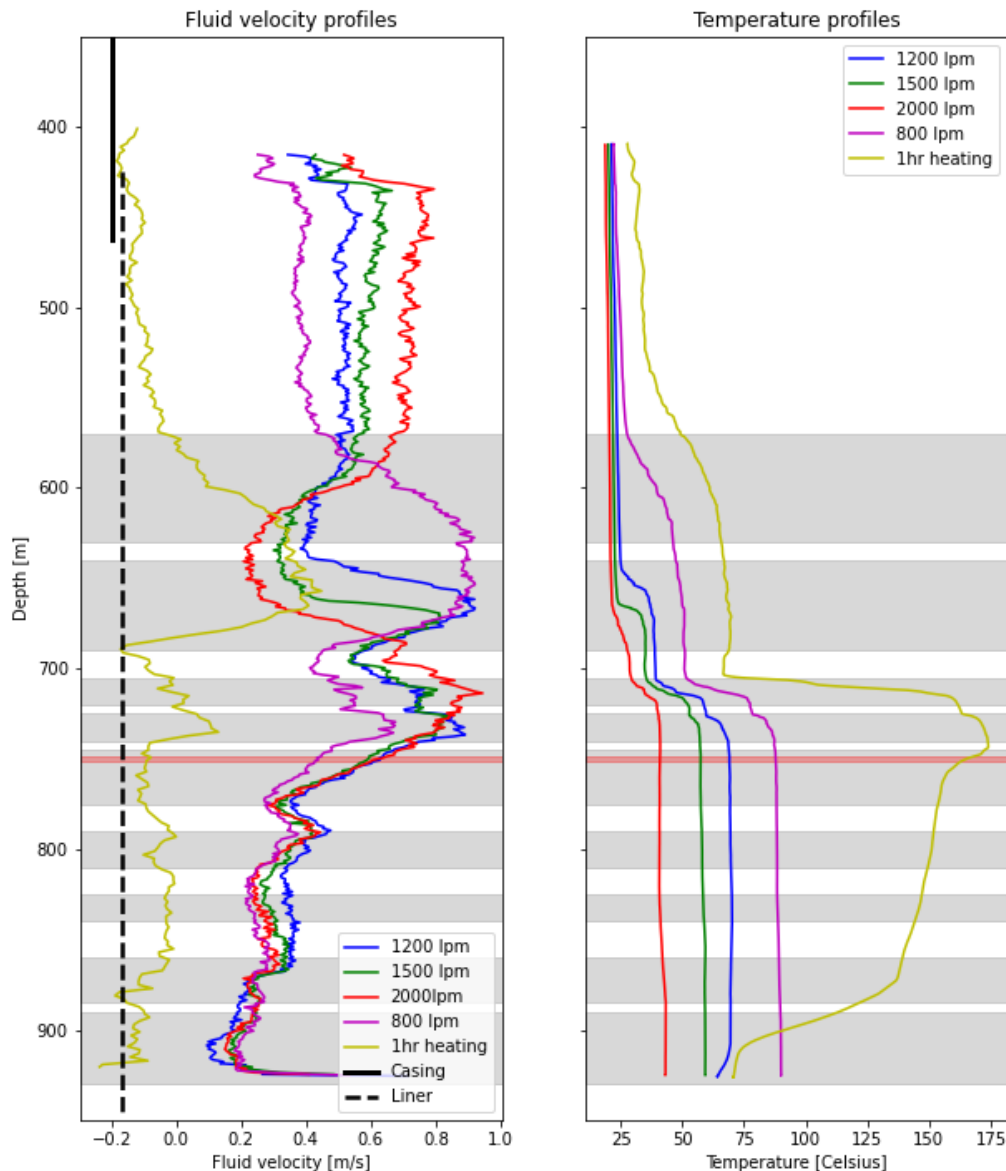


Figure 4: Example of feed zone identification in WK260 (Monday, prior to chemical cleaning), from fluid velocity profiles and temperature profiles, during injection and after 1 hour of heating. Feed zones are indicated by grey shading. The pressure control point (PCP) is indicated in red. The target feed zone for stimulation (FZ5) coincides with PCP.

Table 1: Summary of feed zones in WK260, corresponding to feed zones indicated in Figure 4. Contribution of each feed zone to flow during discharge and magnitudes of inflows/outflows during pre-clean injection testing.

| FZ ID | Depth range (m) | Discharging PTS | | Injection testing pre-clean (Monday) | | |
|-----------------------------|-----------------|--|-------------|--------------------------------------|-------------------------|-----------------------|
| | | Comment and proportion of flow contributed | | Magnitude of inflow/outflow (t/h) | | |
| | | 2014 | 2019 | blue = outflow, yellow = inflow | | |
| | | | | Low flow 1199 lpm | Medium flow 1472 lpm | High flow 2021 lpm |
| FZ1 | 570-630 | None | None | -319 | -958 | -1693 |
| FZ2 | 640-690 | Flowing 35% | Flowing 60% | 415 | 703 | 1342 |
| FZ3 | 705-720 | Flowing 35% | Flowing 40% | 575 | 639 | 128 |
| FZ4 | 725-740 | None | None | 287 | 64 | 128 |
| Target for chemicals FZ5 | 745-775 | Flowing 30% | Blocked 0% | -1342 | -1405 | -1150 |
| FZ6 | 790-810 | None | None | -160 | -64 | -319 |
| FZ7 | 825-840 | None | None | 0* | 0 | 0 |
| FZ8 | 860-885 | None | None | -479 | -224 | -96 |
| FZ9 | 890-TD | None | None | -256 | -224 | -319 |

* FZ7 was inactive during the pre-clean injection testing but was apparent in later testing.

not necessarily the best because large outflows above the target feed zone (FZ5 in this case) can result in insufficient flow and chemicals reaching the target zone. Table 1 indicates that the injection flow rate delivering the greatest flow to the target feed zone is, in fact, the medium flow rate, 1472 lpm. At the highest flow rate, significantly more fluid exits at the shallowest feed zone (FZ1).

4.3 Target Feed Zone

To know your target feed zone, you must identify which of the feed zones have been blocked over time. Prior to the clean, the target feed zone in WK260 was identified using old PTS data from completion testing and discharging PTS data from subsequent output tests. Figure 5 shows fluid velocity profiles during discharge from 2014 and 2019. The sign convention for fluid velocity is negative moving up the wellbore and positive moving down.

Figure 5 shows that three of the feed zones identified during injection testing (see Figure 4) contributed to flow during discharge: FZ2, FZ3 and FZ5. The primary target for chemical stimulation is FZ5, as it was active in 2014 when it contributed around one-third of the well flow (Table 1) but became blocked by 2019.

It can be seen in the discharging profiles shown in Figure 5, although the flow was greater in 2019 (190 t/h) than in 2014 (171 t/h), the well was still in worse condition in 2019. Flow rate alone is not an indication of well condition. In 2019 the wellhead pressure (WHP) was much lower, and the enthalpy dropped from 1327 to 1073 kJ/kg. The change in enthalpy explains the very large difference in fluid velocity for similar flow rates. Steam takes up far more volume than water. Therefore, to achieve the same mass flow rate, higher enthalpy fluid, which contains more steam, must move at a much higher velocity than lower enthalpy fluid, which contains more water.

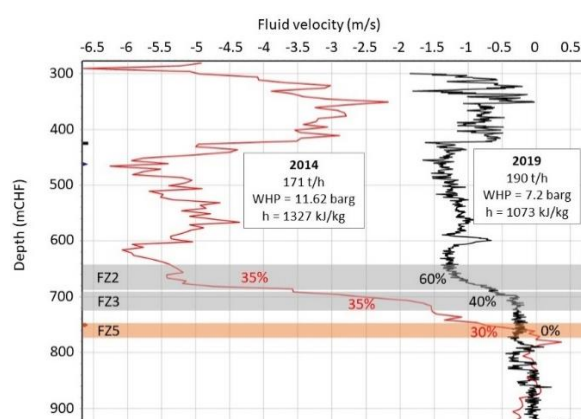


Figure 5: Discharging fluid velocity profiles in WK260: from 2014 (red), prior to scaling; and from 2019 (black), immediately prior to failure to return to service.

4.4 Dilution of Chemicals

Knowing the magnitudes of the inflows and outflows allows us to calculate, using a simple mass balance, the change in concentration of the chemicals as they travel down the well. Inflows dilute the chemicals, while outflows have no effect on concentrations. Flow data can confirm not only that flow is reaching the target feed zone but also that the chemical concentration remains sufficient to be effective. Table 2 provides an example of the medium injection rate conditions on Monday, prior to the chemical cleaning (see Table 1).

Table 2: Change in chemical concentration at each feed zone, for an initial concentration of 10.0 and flow conditions for the medium injection flow rate in Table 1.

| FZ ID | Inflow/outflow at FZ (t/h) | Flow lpm | Chemical conc. | Comment |
|----------|----------------------------|----------|----------------|-----------------------|
| @Surface | - | 1472 | 10.0 | - |
| FZ1 | -958 | 514 | 10.0 | No change |
| FZ2 | 703 | 1217 | 4.2 | Dilutes with inflow |
| FZ3 | 639 | 1856 | 2.8 | Dilutes with inflow |
| FZ4 | 64 | 1920 | 2.7 | Dilutes with inflow |
| FZ5 | -1405 | 515 | 2.7 | TARGET – 2.5 % at FZ5 |
| FZ6 | -64 | 451 | 2.7 | No change |
| FZ7 | 0 | 451 | 2.7 | No change |
| FZ8 | -224 | 227 | 2.7 | No change |
| FZ9 | -224 | 3 | 2.7 | No change |

4.5 Injectivity Index

Because WK260 is a production well, the only definitive assessment of the effectiveness of the stimulation came from output data (see Section 4.6). However, after cold water injection, it takes several weeks or months for a well to heat up and permit output testing. Injectivity index (II) provides an early indication of the impact of the stimulation (and is much quicker and easier for cleaning jobs that include injection testing).

The II is difficult to assess with accuracy in highly permeable wells such as WK260, because the pressure changes associated with the changes in flow rate are very small, in this case, a fraction of 1 bar. However, with careful data analysis, it is possible to get a reasonable indication of injectivity shown graphically in Figure 6. The II was assessed at 780 m, within the target feed zone (FZ5):

1. 93 t/h/bar on Monday: pre-stimulation.
2. Acid stimulation on Tuesday.
3. 189 t/h/bar on Wednesday: post-acid step (an increase of 103% compared to Monday).
4. Caustic stimulation on Thursday.
5. 241 t/h/bar on Friday: post-caustic II (an increase of 159% compared to Monday, which is an incremental increase of 56% related to the caustic step on Wednesday)

These results confirmed that, by dissolving scale or other minerals in the formation, the acid and caustic steps produced a significant increase in permeability.

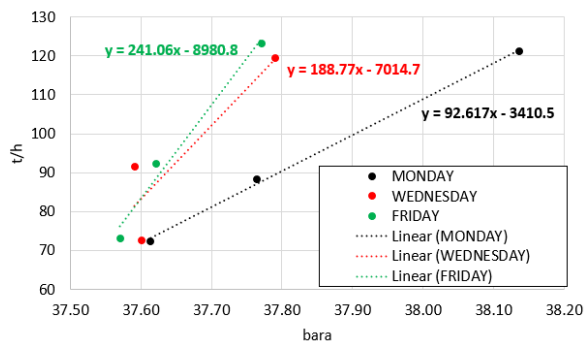


Figure 6: Injectivity index plot for WK260, at a depth of 780 m.

4.6 Output Testing

Output curves (mass flow vs WHP) are the usual method to characterise the condition of the well. Figure 7 shows the progressive change in output curves for WK260 through time, summarised as follows:

1. 2011 to 2015: Curves nested within each other, and maximum discharge pressure (MDP) decreases, indicating reservoir pressure decline.
2. 2015 to 2019: MDP remained constant, indicating the decline in the well output was not related to the decline in reservoir pressure but rather to scaling in the reservoir.
3. 2016 to 2018: The reservoir pressure decline stabilises, and the well consistently produces 300 t/h while online.
4. 2019: The output has declined drastically, and the well could not be returned to service after output testing.

5. 15-17 December 2020, the week after chemical cleaning. The well is flowing through a silencer and is heating up. Spot checks of output show the progressive heat up of the well. Unfortunately heat up is slowed down as the well is shut in shortly afterwards for unrelated operational reasons.
6. 23 June 2021: output testing to silencer reveals the output has recovered to the expected 2016-2018 levels (100% recovery).

These output results from WK260 indicate a significant increase in output to the maximum expected recoverable output (2016-2018 levels, after the reservoir pressure decline stabilised).

There was a time gap of ~ six months between the December 2020 spot checks and June 2021 data due to unavoidable operational reasons. The progression of the heat up data from December 2020 does tend to indicate that with further heating (the well was not fully heated at this stage), the output is likely to go beyond the expected 2016-2018 level. This would imply two things:

- The well output after cleaning may have exceeded the 100% expected capacity. This implies some stimulation of the formation by the chemicals (mineral dissolution).
- The 2021 data point would therefore indicate the output has declined back to 2016-2018 levels due to the buildup of new scale.

The potential for production well stimulation by mineral dissolution using this cleaning method is of significant interest and will be the focus of future work. Stimulation of the formation has been observed in reinjection wells using this cleaning method (Muller et al., 2021).

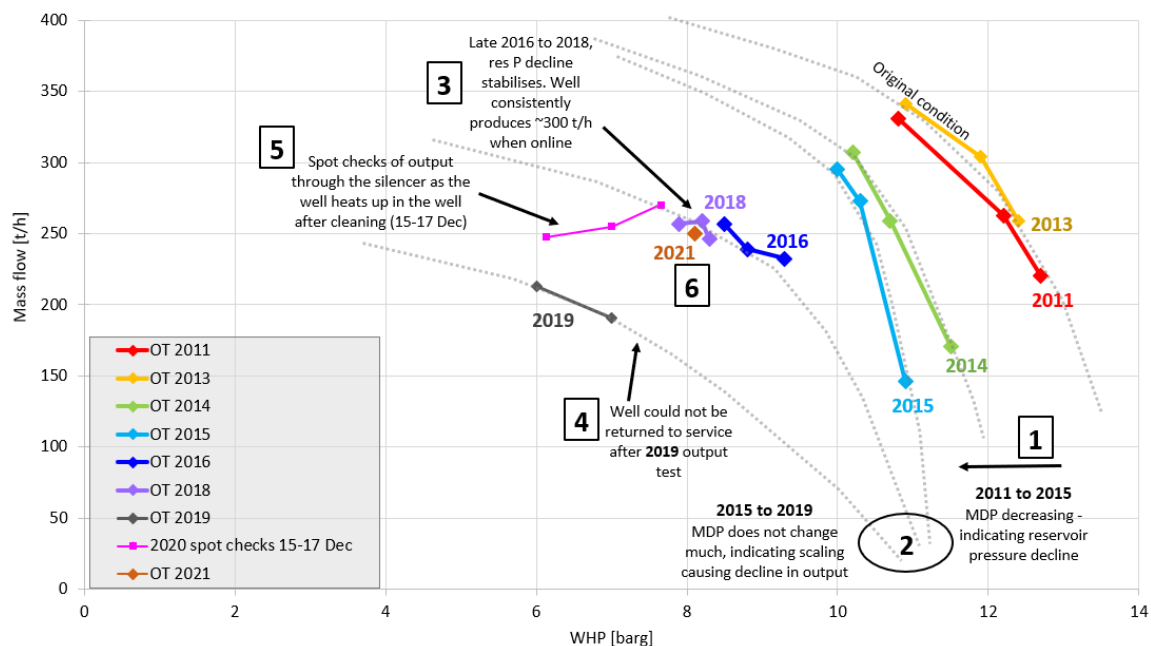


Figure 7: WK260 output curves 2011 to 2021 showing the progression of reservoir pressure decline (unrecoverable for the purposes of chemical cleaning), progression of decrease due to scaling (recoverable), and recovery after chemical cleaning.

5. CONCLUSIONS

The acid/caustic chemical clean of WK260 was a success, recovering 100% of the expected capacity. There are indications it may have exceeded this capacity for a time, which implies some level of stimulation of the formation. This is of significant interest and will be the focus of future work.

WK260 was of particular technical interest because of its complicated well dynamics. Understanding the behaviour of the well's feed zones at different injection rates was critical to ensuring the chemicals reached the target feed zone in sufficiently high concentrations to be effective. This required extensive PTS testing before, during and after the chemical cleaning job. The conclusions from this PTS testing are:

- Many geothermal wells have multiple feed zones, with inflows and outflows that have the potential to compromise the delivery of flow and chemicals to the target feed zone(s).
- Outflows above the target feed zone have the potential to divert too much flow, but diversion can be minimised with careful selection of injection flow rate. The highest flow rate is not necessarily the best. For WK260 the medium injection rate was most effective at delivering chemicals to the target feed zone.
- Inflows above the target feed zone dilute the chemicals. Dilution can be assessed using a mass balance down the length of the well. Assessing dilution can provide assurance that the chemicals are reaching the target feed zone in sufficient concentrations.
- The acid and caustic steps are both effective in increasing permeability (when coupled with sequestrants and polymers targeted at preventing redeposition) as revealed by increases in the injectivity index after each step.

The role of the additives to the base acids and caustic is key to preventing redeposition of scales. The additives must be chosen after careful brine and scale analyses.

Compared with traditional methods, this process includes the use of more environmentally friendly and safer chemicals and an improved understanding of well flow responses. Bull heading of chemicals from the surface at relatively high flow rates is key to success, as spotting chemicals at low flow rates with CTUs is not effective.

This production well cleaning method is far less expensive compared with alternative technologies or drilling new wells and is a significant step forward for the geothermal industry.

6. REFERENCES

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