GRC Transactions, Vol. 45, 2021

# Case Study: Online Geothermal Well Stimulation and Silica-Based Formation Scale Removal

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**Keywords**

*Online Chemical Cleaning, Silica Scaling, Reinjection Wells, Geothermal Well Stimulation*

## ABSTRACT

Silica remains one of the prominent problems that cause the loss of capacity in geothermal reinjection systems. Until recently, no solutions were available to stimulate or completely recover reinjection capacity if the formation beyond the wellbore was scaled with silica or silicon-based deposits.

Historically, in New Zealand, hydrofluoric acid (HF) or mud acid was used to try to improve and recover reinjection well capacity; however, the risk to the assets, the cost of the application, the risk to the environment, and the risk posed to the people doing the job did not warrant the short-term and marginal results achieved using the HF intervention.

Recently, an application approach and chemistries that often enable geothermal operators to recover full capacity of their reinjection systems were developed. This new technique has many advantages over traditional methods. Advantages include avoiding the need to shut down the well; reducing cleaning time to two days during full and normal operation; using far lower concentrations of chemicals; and recovering, in many cases, well capacity that exceeds 100% of the full historical capacity.

One of the world's leading geothermal operators invested significant resources into the understanding of this new method and thus has been able to contribute to the collaborative advancement of this technique to the wider geothermal industry.

This paper documents three case histories using this new online well stimulation process and includes a comparison with offline cleans using HF. The geothermal company reviewed the two methods and found that the online method was at a minimum 13 times better in terms of ROI and benefits than off-line techniques.

## 1. Introduction

As previously documented in Muller and Wilson (2019), Solenis LLC and Thermal Clean Ltd developed a method of cleaning and stimulating reinjection wells. This method was developed based on research and development into the root causes of silica deposition. For many years, we thought that amorphous silica polymerisation was the issue. However, upon investigation, we found that cations catalysed silica polymerization and worsened the issue.

Contact Energy Ltd owns Wairakei Power Station. As one of the longest producing geothermal plants in the world, it has experienced almost every problem that can arise during the production of electricity from a geothermal source. One of the key pieces of information Contact Energy contributed to the initial project was the calculation of amorphous silica polymerisation times. These polymerisation times were far too long; clearly other factors were at play.

Contact Energy dedicated some of its key personnel with significant experience in well intervention and reservoir engineering to investigate the mechanics of and to understand the rationale for the success of this online method. Contact Energy and Solenis are collaborating in an R&D partnership to understand and develop this process. Contact Energy now adopts the online clean process as a key part of its routine maintenance program. This paper outlines cleaning and stimulation case studies for three reinjection wells from the Wairakei and Ohaaki Geothermal Fields: WK310, WK304 and BR55. The case studies include permeability analyses, which were used to better understand the effectiveness of this intervention process.

## 2. Reinjection Well WK310

WK310 is a deviated reinjection well in the Otupu reinjection area of the Wairakei Geothermal Field (see Figure 1). WK310 was drilled in 1995 to a depth of 2238 metres from casing head flange (mCHF) and was cased to a depth of 609 mCHF. Little data are available on the original condition of the well (in 1995) because its high deviation prevented downhole pressure-temperature-spinner (PTS) tools from being run on wireline. However, with technology improvements and perseverance, PTS injection testing was successfully undertaken in August 2012 and again in March 2015. In 2018, an HF clean was performed on WK310, mainly to assist wireline tool fishing. The clean yielded a small but temporary (not longer than a month) increase in injectivity index (II).

WK310 has three permeable feed zones (see Figure 2 and Table 1). The deeper two feed zones, FZ2 and FZ3, were active in 2012 and accepted all of the injected fluid. By 2015 they were partially blocked; combined, they accepted only approximately 26% of the injected fluid. A new path of least resistance, a slightly shallower feed zone (FZ1), which had not been active in 2012, had developed at about 1600 mCHF. Figure 2b,c show that injecting temperature profiles are not a good indication of permeable feed zones. These profiles are relatively featureless because the well has been in active service for many years, cooling and stabilising the reservoir around the well.

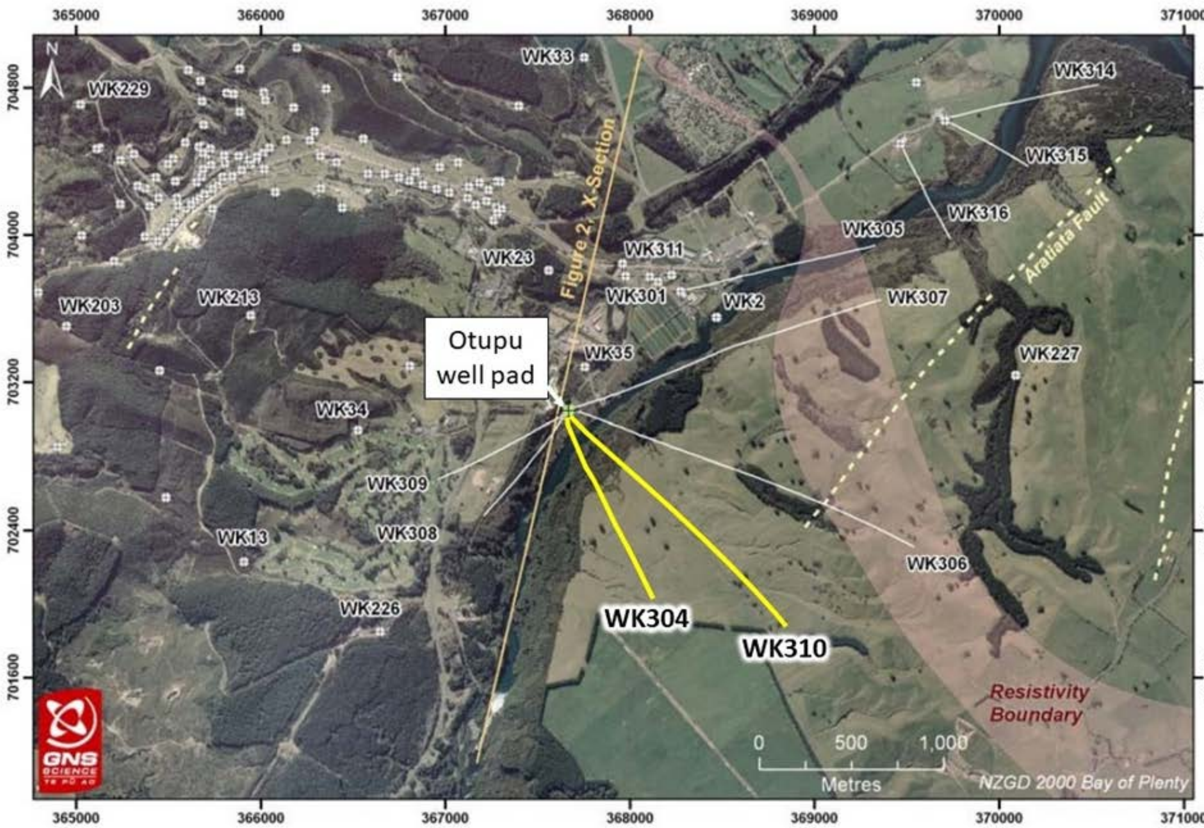


**Figure 1: Aerial photo showing location of Otupu reinjection well pad and radiating, deviated well tracks; WK310 and WK304 are highlighted. Modified from Milicich et al. (2010).**

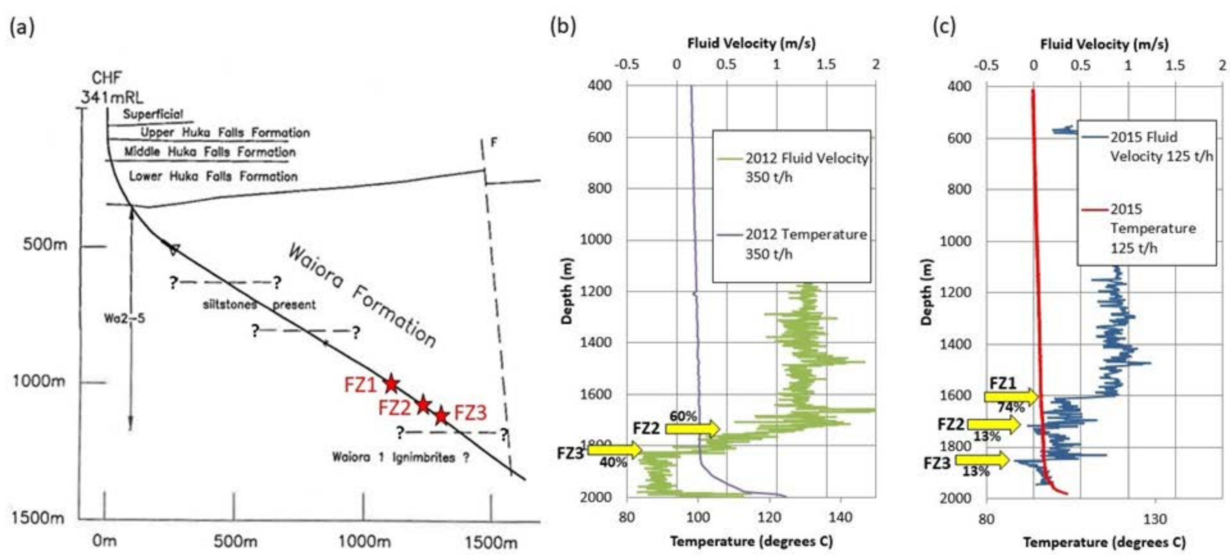


**Figure 2: Feed zones of Table 1 indicated in: (a) geological cross section along the line of WK310 (modified from original geology report in Wood, 1995); (b) 2012 fluid velocity and temperature profiles at 350 t/h injection; (c) 2015 fluid velocity and temperature profiles at 125 t/h injection.**

**Table 1: Summary of WK310 Feed Zones in 2012 and 2015**

| Feed zone ID | Depth interval (mCHF) | Thickness (m) | 2012 % of total flow (250 t/h) | 2015 % of total flow (125 t/h) |
|---|---|---|---|---|
| FZ1 | 1600 - 1620 | 20 | 0 – not observed | 74 |
| FZ2 | 1730 - 1760 | 30 | 60 | 13 |
| FZ3 | 1820 - 1850 | 30 | 40 | 13 |

### *2.1 WK310: Well Geology*

The open-hole interval in WK310 is located within the Waiora Formation (Wood, 1995) and underlies the Huka Falls Formation sedimentary caprock (see Figure 3; Bignall et al., 2010). The Waiora Formation, which is extensive throughout the Wairakei-Tauhara geothermal system, is a sequence of volcanic deposits (ignimbrite, vitric tuff and breccia) interlayered with fine sedimentary units of mudstone and sandstone (Bignall et al., 2010; Bromley et al., 2021). In the original geology report, Wood (1995) describes a 500-metre-thick sequence of tuff from 1200 to 1900 mCHF. Tuffs are a rock type that forms by the deposition of volcanic ash that is ejected during a volcanic eruption. The particular type of tuff present, vitric, is composed primarily of fragments of rhyolitic (high silica) volcanic glass. Wood (1995) notes that the lithological boundaries are difficult to identify with accuracy below 1400 mCHF because vitric tuff is a relatively soft rock type and beyond this depth, the cuttings are extremely fine-grained and difficult to identify.

All three feed zones lie within the interval of rhyolitic (high silica) fine-grained vitric tuff within the Waiora Formation. Thus, the caustic clean likely has been effective in dissolving not only silica scale, but also the very fine-grained, high-silica ash deposit (tuff).

II can be tracked in real time from the flow (t/h), WHP (bar) and injection temperature (°C) data, which are constantly measured for injection wells. Variations in injectate temperature cause variations in injectivity that are unrelated to any actual change in reservoir permeability. Therefore, to observe any trends in the reservoir data, we must correct the II to a single temperature (Siega et al. (2014). In 2011 the WK310 II for 120 °C brine was 22 t/h/bar, but by 2020 this had declined to roughly 4 t/h/bar. The reduction in II was due to a combination of amorphous silica and silicate deposits, which were confirmed by analysis of samples taken from the reinjection line.

### *2.2 WK310: Chemical Cleaning*

After this well's first cleaning in July 2020, its II for 120 °C brine peaked at about 16 t/h/bar before stabilising, after 1 month, at about 12 t/h/bar. To initiate flow, cold water stimulation was used a week prior to the start of the cleaning, allowing enough flow of geothermal fluid to begin treatment. In terms of flow rate, prior to the clean the well could only accept approximately 40 t/h, peaking at more than 180 t/h before stabilising at approximately 145 t/h after one month (see Figure 4). This well had been a candidate for abandonment prior to the clean, so the result was very pleasing to Contact Energy.

To gain a full picture of the effect of stimulation on the reservoir (injectivity/permeability), we must consider both flow rate (t/h) and well head pressure (WHP, barg). An increase in flow rate does not necessarily mean an increase in injectivity/permeability, because an increase in injectivity/permeability can be achieved by increasing the WHP (application of a higher pressure on the formation). However, an increase in flow rate is an indication of an increase in injectivity/permeability if the WHP remains constant (applying the same pressure on the formation while achieving a higher flow rate). Similarly, if the WHP decreases (less force is applied on the formation), but the flow rate increases, then the increase in injectivity/permeability is even greater. For the chemical stimulation jobs discussed in this paper, the WHP remained constant or decreased during each application, which signifies that the observed increases in flow rate are indicative of real increases in injectivity/permeability.

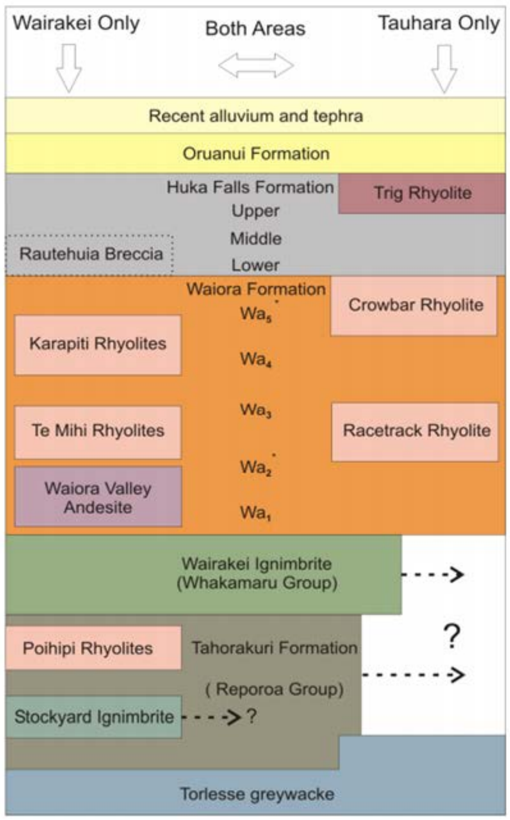


**Figure 3: Stratigraphy of Wairakei-Tauhara geothermal system (Bignall et al., 2010).**

The wells at the Otupu reinjection site can be fed from flash plants (approximately 130 °C fluid at 6 bar) or from the Wairakei Binary Plant (approximately 90 °C fluid at 2 bar). Temperature affects permeability. Cooler temperatures are thought to cause thermal contraction of the rocks, which increases porosity and permeability. Related directly to chemical cleaning, the temperature also affects the reaction kinetics of cleaning chemistries. Therefore, temperature is always maximised with the hottest fluid available during chemical stimulation jobs. Thus, the ideal procedure is first to stimulate the wells with cold water, to improve access for the chemicals into the scaled formation, and then to inject the chemicals using the hottest fluids available, to maximise the rate of reaction.

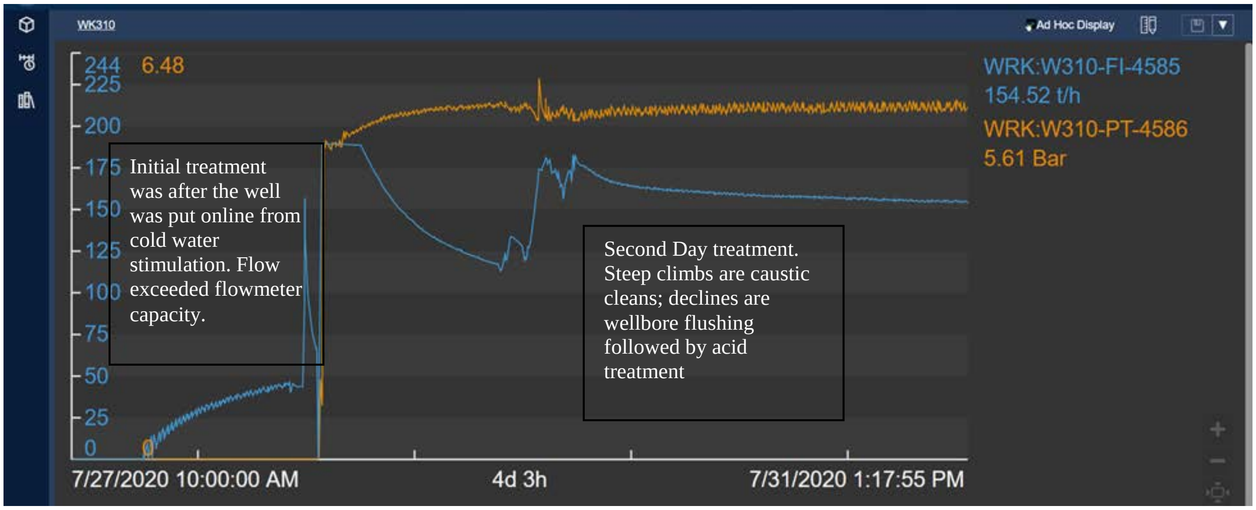


**Figure 4: First clean July 2020; No flow to 180 t/h.**

Given our successes recovering other reinjection and production wells, we revisited WK310 in February 2021. The well had continued to accept fluid, but its capacity had declined to 70 t/h because of the usual scaling tendency of the brine. We decided to complete six cycles of the online injection program and again used the oscillation technique (oscillating between inhibited acid and alkaline sequestrants). During the three-day clean, a peak flow rate of 270 t/h was achieved (see Figure 5). The II prior to the clean was about 7 t/h/bar (for 120 °C brine). Following the clean, the II peaked at 32 t/h/bar, greater than the original 2011 II of 22 t/h/bar, before declining to about 20 t/h/bar after approximately one month of operational service. These results suggest not only that the deposited silica was removed, but also that the surrounding formation was stimulated.

Because this was the third example of a reinjection well accepting greater than its expected maximum capacity after a clean, we explored formation types and structures further to see if we could better predict which wells could achieve this result. On the basis of these experiences, WK304 was re-cleaned.

## 3. Reinjection Well WK304

WK304 is also a deviated reinjection well in the Otupu reinjection area of the Wairakei Geothermal Field (see Figure 1). It was drilled in 1990 to a depth of 1467 mCHF and was cased to a depth of 641 mCHF. For the same reasons identified for WK310, little data are available on the original condition of WK304. Two unsuccessful logging attempts were made to the well since 2012, before success was achieved in 2017, although by that time the injectivity had declined drastically.

In the 2017 injection PTS data for WK304, one permeable feed zone was apparent, revealed by a sharp drop in fluid velocity and a sharp rise in temperature at 1190–1200 CHF (see Figure 6). During a previous attempt at PTS testing in 2012, there was an indication that a single feed zone may exist near 1300 mCHF, which would imply this deeper zone had blocked completely, forcing fluid out near 1200 mCHF instead. However, the data quality of that earlier test was so poor that no conclusion could be drawn with any degree of confidence.

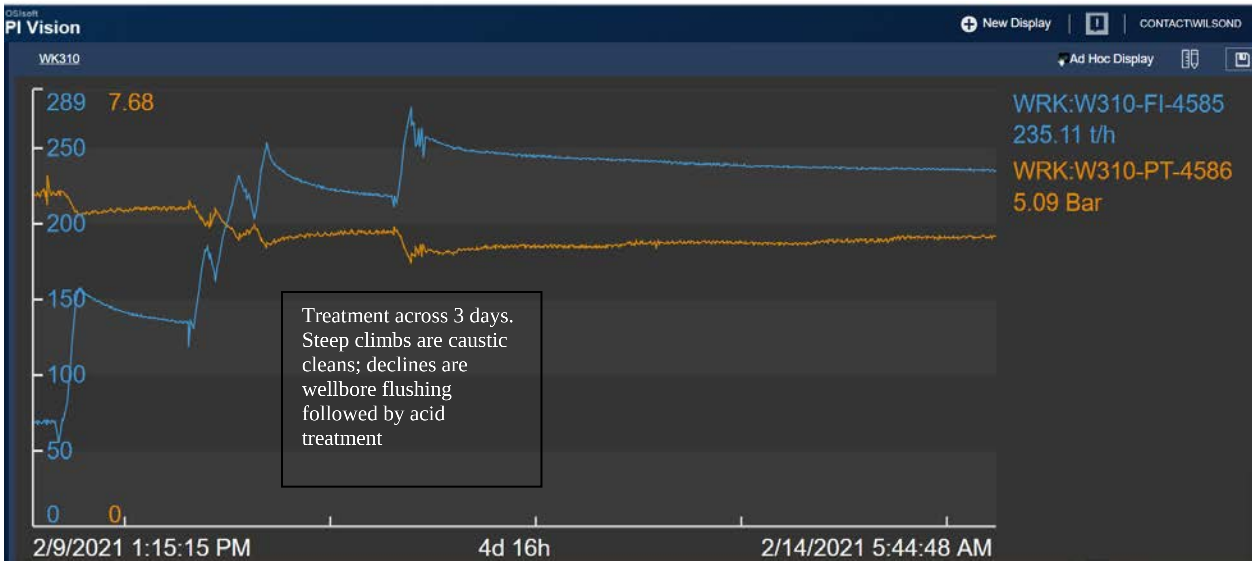


**Figure 5: WK310 second clean February 2021; 70 t/h to 270 t/h.**

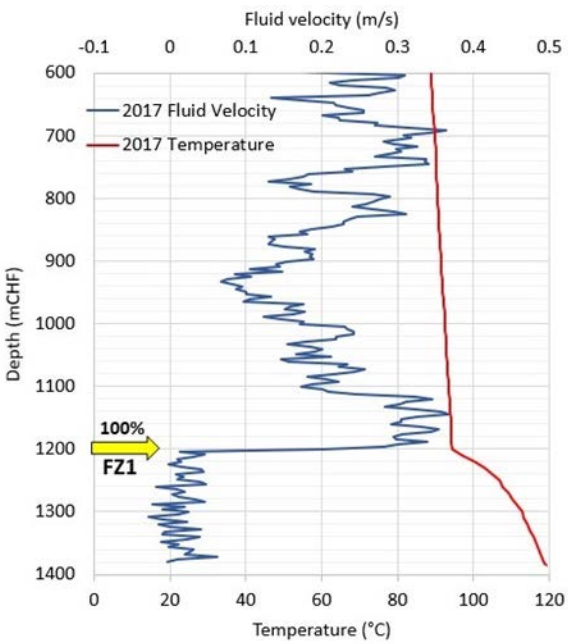


**Figure 6: WK304 fluid velocity and temperature profiles at 23 t/h injection in 2017.**

### *3.1 WK304: Well Geology*

Although little geological information is available for WK304 because it is an older well, it is in the close vicinity of WK310 and the rock types are very similar. The geological model of the

Otupu area is well defined by the surrounding wells. As is the case for WK310, the feed zone in WK304, although shallower, is located in the Waiora Formation. The presence of vitric tuff and carbonaceous siltstone is also noted at similar depths in the nearby WK317 reinjection well (drilled vertically from the Otupu well pad shown in Figure 1).

### *3.2 WK304: Chemical Cleaning*

WK304 was cleaned twice using the online method, once in July 2020 and once in February 2021. Prior to those online cleanings, it was cleaned in 2018 with HF through a coil tubing unit (CTU). The maximum flow that was achieved during this clean was 80 t/h, but the flow quickly, within just a few months, declined to zero. After this HF clean, the well was left shut in and it became a candidate for abandonment because it was unable to contribute to the required reinjection need of the power station.

WK304 had been on binary plant service (approximately 90 °C fluid at 2 bar) for several years prior to treatment although it had been shut in and unable to accept fluid for two months prior to the first clean. To increase the effectiveness of the treatment, we switched WK304 to hotter fluid six days before treatment. Initial flow at the time of treatment was about 65 t/h. Response to the two-day treatment was rapid. The treatment consisted of four cycles of oscillation of the alkali sequestrant and inhibited acidic formulations. The maximum reinjection flow obtained was 155 t/h. The flow settled a few days later to 140 t/h (see Figure 7).

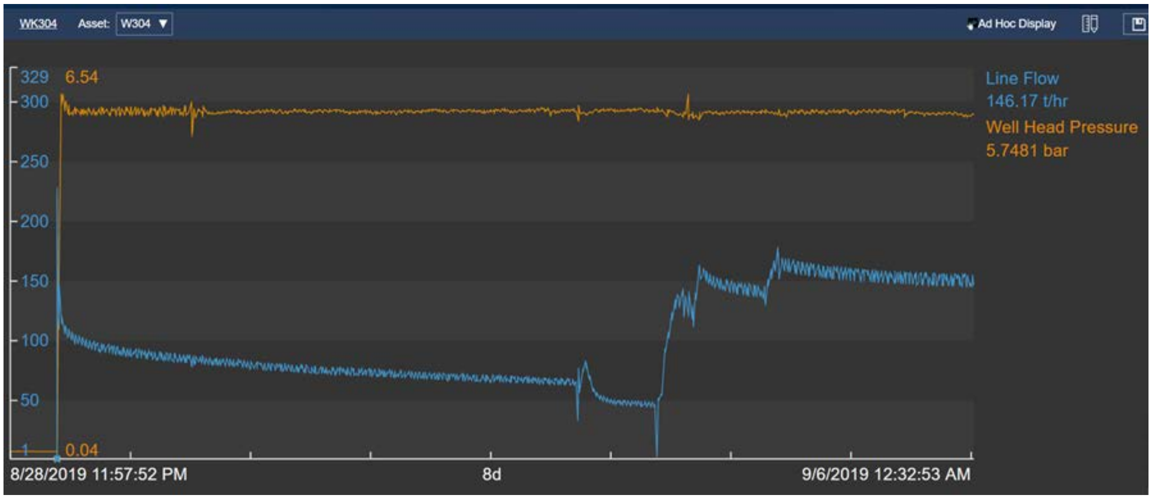


**Figure 7: WK304 first clean; recovering from 65 t/h to 140 t/h.**

On the basis of the results of previous wells, such as WK310, we performed another online clean in April 2021 (see Figure 8). Again, six oscillations were conducted on WK304, similar to the treatment for WK310. However, WK304 did not experience as large of an improvement as WK310 even though the effectiveness of the second clean was greater than for the first clean (greater increase in injectivity vs amount of chemical used). Again, WK304 had been on binary plant service prior to being placed on hotter fluid.

The formation geology and the structure of the feed zones were examined for WK310 and WK304 and were found to be very similar. The differences in the effectiveness of the chemical cleanings (WK310 was a little more effective than WK304) were likely because WK304 had been left longer between cleanings. Therefore, some of the original feed zone was blocked completely and was unable to be opened by the combination of the cold-water stimulation and the online clean process. Thermal effects may have had an impact because the ambient temperature, approximately 90 °C, was cooler than the fluid coming directly from the flash plant, approximately 130 °C. The implications of these factors will be discussed in section 5. Discussion and Conclusions.

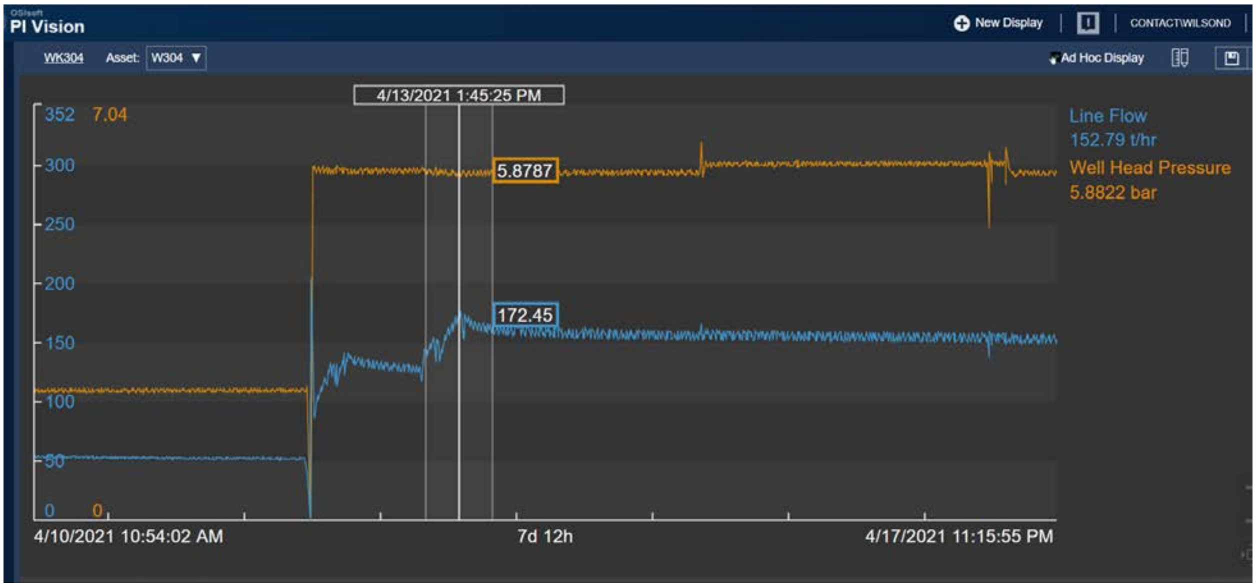


**Figure 8: WK304 second clean.**

## 4. Reinjection Well BR55

BR55 is a shallow vertical reinjection well in the Northwest reinjection area of the Ohaaki Geothermal Field (see Figure 9). It was drilled in 2007 to a depth of 639 mCHF and was cased to a depth of 178 mCHF.

BR55 has two permeable feed zones, one at about 270 mCHF and the other at about 500 mCHF. These feed zones were identified from the 2007 completion test data by the decreases in fluid velocity and the temperature anomalies at these depths.

### *4.1 BR55: Well Geology*

BR55 targeted and intersected the Broadlands Rhyolite (from 265 to 640 mCHF), which was known from experience with nearby wells BR37 and BR41 (see Figure 9) to be a good target for injection. Both BR55 feed zones lie within the rhyolite; the upper feed zone corresponds to the brecciated upper part of the rhyolite lava body, and the lower feed zone to the middle of the lava body. The Broadlands Rhyolite intrudes into the Waiora Formation and underlies the Huka Falls Formation, in a manner similar to other rhyolite bodies indicated in Figure 3 for Wairakei-Tauhara. Bignall et al. (2007) describe this formation as coherent and massive crystal-rich rhyolite lava, with quartz and feldspar phenocrysts in a microcrystalline groundmass. The formation is weakly to moderately altered with minor quartz, chlorite and pyrite.

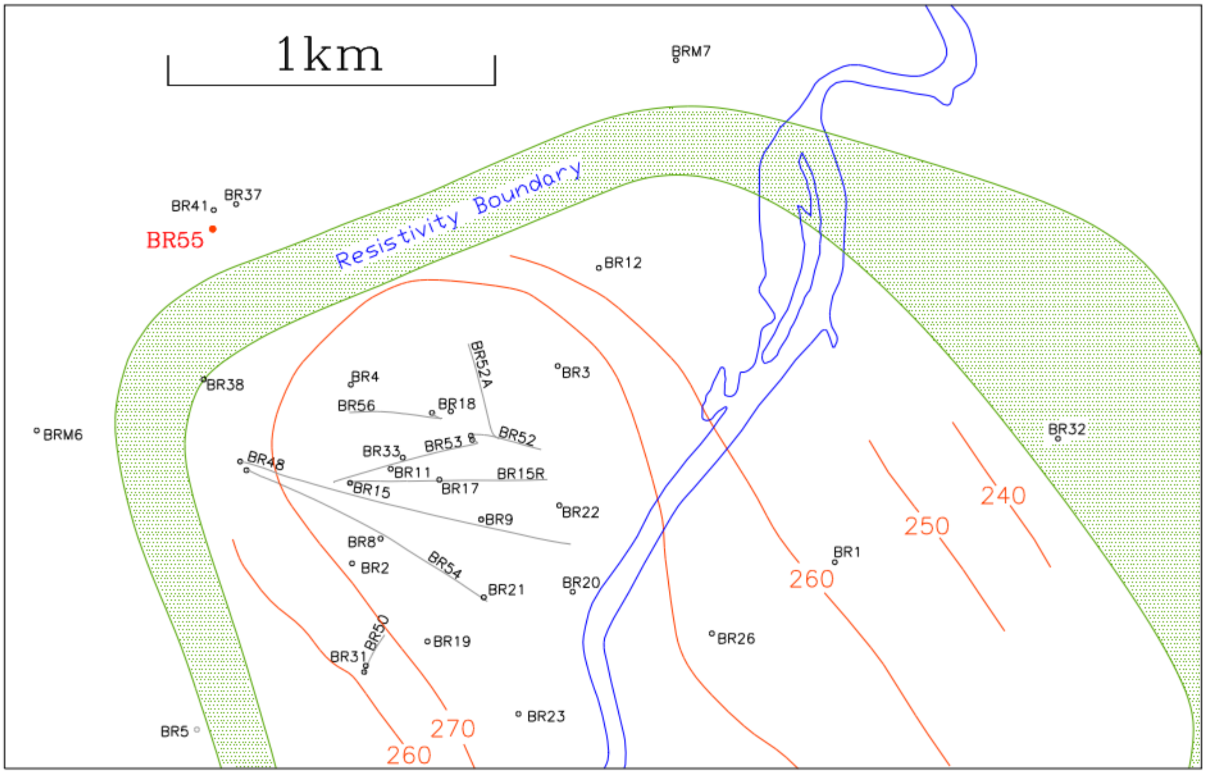


**Figure 9: Map of well locations showing BR55 in the Northwest reinjection area beyond the Ohaaki Geothermal Field resistivity boundary (Bignall et al., 2007).**

### *4.2 BR55: Chemical Cleaning*

BRR55 has additional complexities that must be considered. The silica saturation is higher in the Ohaaki Geothermal Field than in the Wairakei Geothermal Field. The reinjection line needs to be throttled to bring the reinjection pressure down from 30 bar to a maximum of seven bar. Throttling is required because the original Ohaaki plant design was for much higher wellhead pressures in the reinjection system. In 2018 the well was essentially blocked, accepting 10 to 15 t/h of brine. The initial clean used a two-step process and the well reached a maximum capacity acceptance of 240 t/h. Flow rate declined over four months and then stabilised at approximately 60 t/h until the well was shut in after a new well was drilled. In 2019 we performed a clean similar to the first round, achieving a maximum of 375 t/h. Note that 90% of this capacity was achieved using about 20% of the treatment fluid.

In January 2021 we used a modified technique of completing several oscillations of the treatment process over two days to see how much we could improve BR55's capacity. As shown in Figure 10, the maximum acceptance reached was 509 t/h, some 20% higher than the clean performed three years earlier. We used half the treatment volume compared with other cleans in recent years. Again, we achieved approximately 90% of treatment gain using about 20% of treatment fluid.

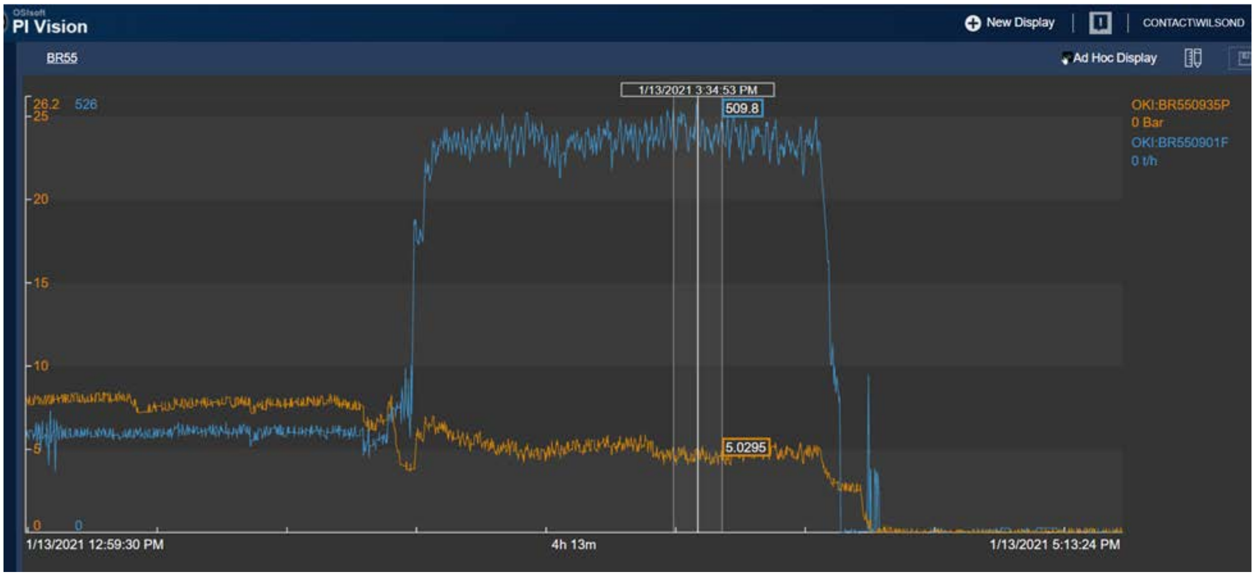


**Figure 10: BR55 second clean; reached 509 t/h.**

The increase in injection performance of this well spiked and declined more quickly than some of the Wairakei wells. (This spike and decline also was observed in BR41 data not shown in this paper.) This spike and decline response may be related to the different lithological units in this well's formations. The relatively coherent crystal-rich rhyolite lava of BR55 is more difficult to dissolve than the weaker volcanic glass in the tuff of WK310 (and likely WK304).

Alternatively, the response may be related to throttling. Because BR55 is throttled (the other wells are not), the pressure drops more, which causes silicates to precipitate. The silicates are nucleation sites for polymerisation of silica; therefore, their presence encourages the growth of silica scale (Newton, 2020). Consequently, BR55 likely experiences scaling closer to the wellbore (or even in the perforations of the liner or the annulus). These deposits are not only more readily dissolved by the chemical cleaning process but also more readily re-deposited, which provides a potential explanation for the sharpness of the peak and decline in this well's performance.

## 5. Discussion and Conclusions

Because of the results we achieved using this online method, we avoided the drilling of at least two new reinjection wells and the abandonment of three others. The online clean method is more cost effective, is easier to apply and produces more sustainable results than using HF or mud acid (see Coutts et al. (2018) for an additional case study with HF cleaning). Online cleaning allows for continued operations and no loss of power generation because no assets are required to be out of service. Additional resources are being devoted to understanding this cleaning method and its benefits to further maximise results and to expand the application into other parts of the company.

From the results we obtained to date from these three case studies, we can conclude that cleaning wells before they completely die provides a definite benefit. A key factor is to have some flow through the formation that allows the chemical to remove silica and silicon-based deposits from the very fine fractures and fissures of the formation. The technique, using pressure and cold water to stimulate an accessible blocked fracture, most definitely works; however, it is far more advantageous to treat a well before it is completely isolated. Treating the cleaning method like a periodic maintenance issue allows operators to eventually reduce treatment chemicals and to gain a better understanding of system dynamics, which could allow optimisation of reinjection systems. In the case of BR55, the impact of throttling tends to support the idea that the cause of accelerated amorphous silica deposition is due to silicate seeding. However, seeded deposition that occurs very close to the wellbore can be relatively easy to remove. We have seen both near wellbore and deeper reservoir improvements in BR55, which is encouraging.

The cost effectiveness of this online method is far greater than any other well intervention method available to date. Further understanding of the mechanisms and variables have enabled us, the collaborators, to stimulate production wells and to clean other areas of geothermal plants affected by silica and silica-based deposits. We intend to continue to explore this method to gain a deeper understanding of its implications, and we plan to report on our findings in the future.

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