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Brine Silica Management at Mighty River Power, New Zealand

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ABSTRACT

Mighty River Power (MRP) along with its joint-venture partners completed the Ngatamariki Power Station Project in 2013, following on the Nga Awa Purua Station Project in 2010 and the Kawerau Station Project in 2008. These plants all feature silica saturation indices (SSI's) of >1.7 using plant design to reduce the risk of silica polymerization and deposition. This allows for additional energy extraction from the same amount of two-phase geothermal fluid.

Through the design phase MRP has looked to form an optimal match between the plant and the geothermal reservoir that supplies it, with silica management forming a significant part. Each project made use of a small test-plant to assess various options to reduce the risks of silica deposition. Two of the recently completed projects are flash plants and make use of pH-modification via sulfuric acid addition to the geothermal brine to inhibit polymerization of silica. The third project uses binary technology and steam-condensate recombined with brine to reduce the pH and to dilute injection fluid, inhibiting the polymerization of silica.

Despite the use of test-plant data and designing the plant for controlling silica polymerization, injectivity declines at one plant led to a requirement for well acid work-overs and a separate project to better understand the root causes of injectivity decline and risks of this at the other plants. Significant investigative work was conducted and a number of operational, plant and process changes were made. One of the key challenges with utilization of pH-modification plants is the need to balance corrosion risk alongside the risk of silica deposition, with appropriate materials being required in high corrosion areas.

This paper discusses various silica management processes, designs and tools employed by MRP across its geothermal plants and some issues that have been identified and rectified.

1. INTRODUCTION

Optimization of all power cycles requires that as much energy is taken from the fluid as is technically and economically feasible. One of the largest limitations on the extraction of energy from geothermal fluid is understanding the lowest temperature the fluid can reach before being returned to the geothermal reservoir. Silica exhibits pro-grade solubility and therefore the cooler the fluid the less soluble the silica, represented by the Silica Saturation Index (SSI) generally given relative to pure amorphous silica. MRP's plants exhibit SSI's of 2.0, 2.3 and 1.9 at reinjection, which by exceeding an SSI of 1.0 allows for additional generation to be achieved for the same geothermal fluid production. This has resulted in the use of pH modification through acid dosing at two flash plants and the use of pH modification and dilution via condensate addition in one binary plant.

Across various geothermal reservoirs the reservoir fluid chemistry and temperature are generally different. Some reservoirs exhibit boiling within the reservoir, resulting in variable discharge enthalpy for the same liquid temperature. Alongside these physical risks there are different reservoir challenges to manage, which means that the design of geothermal stations across different geothermal reservoirs needs to be tailored. Silica management also needs to be tailored to suit, however there are opportunities across multiple plants to develop standard technological tools and methods to both monitor silica management and reduce silica deposition risk within the plant, the wells and in the near wellbore reservoir.

It is important to do as much work as possible up-front to mitigate silica risk. As part of MRP's development strategy, silica management has been given significant consideration to assist with proactive adaptive management. This process includes intensive testing of wells, modeling, design reviews and test-plants. If silica polymerization is not inhibited significant levels of deposition can occur, which may reduce the injectivity of wells and subsequently the output of the geothermal power plant through its inability to inject brine. Monitoring well injectivity, even when a well is under vacuum, can help to enable early warning of silica scaling. Action required once injection wells are affected includes a mechanical work-over of the well, acidizing the well or drilling of a new replacement well.

2. DEVELOPMENT STRATEGY AND SILICA MANAGEMENT OPTIONS

2.1 MRP Development Strategy

MRP has demonstrated a proven geothermal development strategy, where expediency of the development is an important consideration while also managing the risks for reservoir processes and silica scaling.

Recent developments undertaken by MRP and its joint-venture partners have been focused within the Taupo Volcanic Zone in New Zealand: the 100 MWe dual-flash Kawerau geothermal power station commissioned in 2008 , the 138 MWe triple-flash Nga Awa Purua geothermal power station commissioned in 2010 (on the Rotokawa geothermal field) and the 82 MWe binary Ngatamariki geothermal power station commissioned in 2013. These developments followed the purchase and expansion of the Rotokawa geothermal power station (up to 34 MWe) and the buy-in to and expansion of the Tuaropaki Power Company owned Mokai geothermal power station (up to 112 MWe). MRP now operates 470 MW of geothermal power in New Zealand on behalf of itself and its joint-venture partners.

With any development economics need to be considered throughout the whole process. The first major technical consideration for any proposed plant is that the design matches the geothermal reservoir in the long-term. It is important to understand whether the field can withstand less than full reinjection of production fluid, as this can limit the development of evaporative cooling power stations unless additional make-up or cooling water can be sourced. Scaling is then the next major consideration to ensure the power station is operating as efficiently as possible with a high availability factor. The largest constraint with respect to scaling has generally been silica, so by judiciously exceeding the silica solubility of the fluid it is possible to extract additional energy from the reservoir. Exceeding the silica solubility requires processes to be employed such as pH modification, thereby increasing the likelihood and severity of corrosion or other deposition and scaling. Applying higher grade, more costly materials only in where the risk of corrosion is highest helps to ensure that any project remains economically viable. This simplified design consideration process is shown in Figure 1, showing how matching a plant design to reservoir management is the first step, then scaling management and finally corrosion management (materials selection). It is important to note the role of economics across all stages of this development process.

Figure 1: Simplified design consideration process for power station designs.

Throughout the whole development process, time is one of the biggest challenges. Geothermal development requires significant levels of financial input early on in the development process, in particular for well drilling. Capitalized interest can reduce any returns from a geothermal development if the time between significant expenditure and income generation is not minimized. A brief overview of the MRP development process is detailed below, with considerations of silica discussed. The overview in this paper does not include considerations and testing made for obtaining consents for projects or when and how negotiations with plant suppliers occur.

Stage 1 – Obtaining access and early stage geoscience

Access must be obtained for early stage geophysics, geologic mapping and geochemistry sampling of available surface features. If the field is a brownfield, obtaining as much data from existing wells is highly beneficial. Early stage geoscience work enables consideration of the temperature of the reservoir and the size/extent.

Stage 2 – Drilling exploration and initial wells, testing for flow, enthalpy and chemistry

Following the early stage geoscience work, exploration drilling needs to commence to define the size of the field and prove permeability, pressure and temperature. In addition to drilling wells, discharge tests provide constraints on field enthalpy and chemistry; the more wells that are tested the greater the understanding of the variability across the field. Good quality chemistry information, including gas chemistry, enables modeling to occur for various power plant designs.

There is a trade-off between the de-risking of the development (increased information on chemistry, enthalpy and flow by more exploratory wells) and the capitalized interest of having relatively expensive assets prior to revenue generation once a power station has been constructed. Also part of the trade-off is market condition change (price forecasts) where the project is subsequently not feasible; impairments are likely to be a lot higher if more wells have been drilled.

Stage 3 – Interpretation, modeling, fuel plan and identification of key reservoir considerations

Interpretation of the data collected from early stage drilling and well testing allows an initial fuel plan to be developed, with scenario modeling conducted to prove various reservoir production scenarios and reservoir size. Following scenario testing with a reservoir model, future production wells can be identified either in-field (more certain) or step-out (less certain) from the wells drilled. Any key reservoir considerations can be identified such as where injection needs to occur and whether or not full injection is required. These considerations enable an understanding of plant technology options are available.

Variation across the field in physical discharge parameters, such as enthalpy and chemistry, allow the identification of well discharge that is most representative of future production fluids. The identification of likely variation across the field allows for desktop analysis and identification of a particular well for discharge to a test-plant (Stage 5).

Stage 4 – Desktop analysis and review

Desktop analysis and review of various plant designs is conducted by mechanical engineers, chemists and process engineers. Based on the experience of the individuals involved, this desktop analysis will identify any absolute limits in proposed designs and can be used to identify what to model as process conditions throughout the proposed plant design. While the desktop review consists primarily looking at the output, efficiency and scaling potential of the proposed designs, it also includes consideration of the capital cost, the operational complexity and importantly the technological assessment – e.g. looking at whether successful acid dosing had been conducted previously. A good desktop review will reduce costs, both monetary and time, by minimizing plant design testing to a limited number of realistic options (Stage 5).

Stage 5 – Conduct mid-term discharge tests and test-plants

A mid-term discharge test (6-12 months) allows interference test information to be obtained across the field if continuous down hole pressures are collected in the non-producing wells. In addition, chemistry sampling throughout the period of the discharge testing provides information whether the chemistry changes within this time frame, an important learning. The construction of a test-plant reduces the risk of the full-scale power station development and, by gathering reservoir interference information concurrently, testing costs are reduced. Various designs can be tested, as shown in previous test-plant activities undertaken by MRP (Brown & Rock, 2010; Addison & Brown, 2012). Key outcomes from the test plant include silica polymerization times for various exit temperatures and pH for each plant design, acid dosing profiles, scaling rates and an understanding of fluid-rock interaction through a packed bed test. To conduct a meaningful packed bed test, it is important to understand the mineralogy of the formation into which pH modified brine is injected and have samples of this rock or samples analogous to it (Gallup, 2011). Injection formation rocks containing significant calcite or other acid neutralizing minerals may increase the pH of the brine sufficient to prematurely trigger silica polymerization; if this occurs near the wellbore once power production starts this may cause injectivity decline in the formation.

Stage 6 – Refinement of plant size and design

Upon completion of the test plant process and reservoir interference testing, proposed station designs are refined and size of plant confirmed. A finalized injection temperature and a pH set-point are confirmed. Predictions of the chemistry that will be produced by new wells needs to be understood, in addition to predictions based on modeling how the reservoir fluid will evolve. Appropriate levels of design flexibility needs to be made to account for this potential variation and evolution. Therefore designing for an SSI of <1.0 for pure amorphous silica is important, prior to any pH modification or condensate dilution. Additional design considerations and provisions can also be made, with additional injection locations, acid pump delivery volumes, etc. to mitigate uncertainties in the projections.

2.2 Options for Silica Management

The level of energy extraction from produced geothermal fluids is generally controlled by silica rather than other chemical components. Until relatively recently almost all geothermal power developments that reinjected fluid operated by keeping the amorphous silica under-saturated (SSI <1.0) or at low levels of silica saturation (SSI <1.2). There is an opportunity to extract more energy from the same volume of produced geothermal fluids if silica scaling can be controlled to higher SSI levels. Due to the very large volume of geothermal fluid necessary in geothermal power generation, any additional energy extraction (i.e. by SSI >1.2) from the fluids must be relatively cheap.

Options for silica management other than injecting with a low SSI include, but are not limited to, the following:

1) Avoidance of reinjection of the geothermal brines, thereby avoiding the major issue of scaling in reinjection wells. Fluids can sometimes be oversaturated for short periods due to the kinetics of colloid formation and the risk of deposition within the plant and pipework before the discharge of geothermal brine can be minimized. This method requires that there be an acceptable location to discharge the geothermal brine on the surface, which may not be possible due to environmental considerations. Avoidance of reinjection will result in a faster pressure decline within the geothermal reservoir, which may result in an unacceptable decline of the production wells and provide an opportunity for incursion of peripheral fluids which may cool the geothermal reservoir.

2) The use of silica removal equipment, such as the Crystallizer Reactor Clarifiers (CRCs), allowing for fluid temperature to be reduced by removal of all silica above saturation before reinjection of the brine. Generally this has been conducted on fields with high reservoir temperatures in Southern California, USA; where highly saline brines with myriad other metals complicate fluid handling and corrosion potential. This process uses a silica seeding polymerization (the reactor) by the addition of silica particles to oversaturated fluids to promote precipitation on the seed particles rather than on plant component surfaces. The brine is then directed to the clarifier unit where the now larger silica particles are settled and removed from the unit as sludge. Plants that feature CRCs require a large footprint along with alloy materials to handle the fluid, therefore significant additional capital expenditure. Ongoing operational costs are significant for the process, which is further complicated by the co-precipitation of other minerals, some of which can be hazardous.

3) Inhibition of silica polymerization through pH modification, reducing the pH with acid injection at, or before, the point of expected colloid formation. Reducing the pH generally has only a kinetic effect with very minor solubility changes in the pH range (Iler, 1979) in question (from around pH 7.5 – 8.5 to pH 4.5 – 5.0); therefore pH modification only changes the time before the silica polymerizes. The reactions responsible for scale deposition must be slowed for a sufficient time to allow brine to migrate deep into injection formations before polymerization occurs. Acid is typically added to single-phase geothermal brine (sulfuric acid or hydrochloric acid if there is a risk of anhydrite deposition) based on flow and pH measurement. Injection of acid-forming vent gases into the brine has also been attempted, however one downside observed was gas returns to production resulted in the gas extraction system of the turbine and condensers being overwhelmed. Addition of low-pH steam condensate is often used in binary plants or flash plants where shell and tube condensers are utilized. As the pH is reduced, the risk of corrosion for carbon steel increases. The reduction in pH in brines that are reduced to low temperatures, for instance in binary plant heat exchangers, can lead to the possibility of other species depositing such as antimony sulfide or arsenic sulfide. Recent developments in New Zealand have utilized pH modification.

4) Increasing pH to increase silica solubility through the addition of an alkali such as sodium hydroxide. By increasing the pH of the geothermal brine, dissolved silicic acid can be converted to the silicate ion. Increasing pH in fluids can be advantageous for corrosion risk (Lichti et al., 2010) and is commonly used in thermal power station cycle chemistry to significantly reduce iron solubility in feed-water. A major drawback is the relative cost of the alkali and the risk of deposition of other minerals within the reservoir caused by water-rock interactions (Mountain et al., 2013). This method is not currently utilized in any operating plant around the world known to the authors.

5) Anti-scalant addition that either functions as a crystal modifier or a dispersant. While this technology is well proven in low temperature and low concentration conditions such as cooling towers, boiler waters or reverse osmosis plants, it is not proven for general silica control in geothermal plants. Anti-scalants are generally less hazardous than concentrated acid and much less corrosive to materials, however the costs of the product can be significant.

6) Dilution with steam condensate is a process frequently utilized in binary or combined-cycle geothermal power stations. The addition of condensate at ≥100˚C can significantly reduce the SSI of the fluid. Addition of lower temperature condensate from flash plant condensate can also be conducted; however this fluid is not highly effective in the reduction of the SSI due to lowering temperature of the brine. The condensate also needs to be de-aerated to prevent excessive corrosion within the pipework or wellbore, therefore the source needs to be protected from aeration such as in a cooling tower.

MRP makes use of pH modification both through sulfuric acid addition and steam condensate addition. Dilution is also utilized in binary and hybrid (binary and steam turbine) geothermal power stations. A number of anti-scalants have been tested, however these were deemed to not be a viable replacement of pH modification for the purpose of silica management.

3. RECENT DEVELOPMENTS

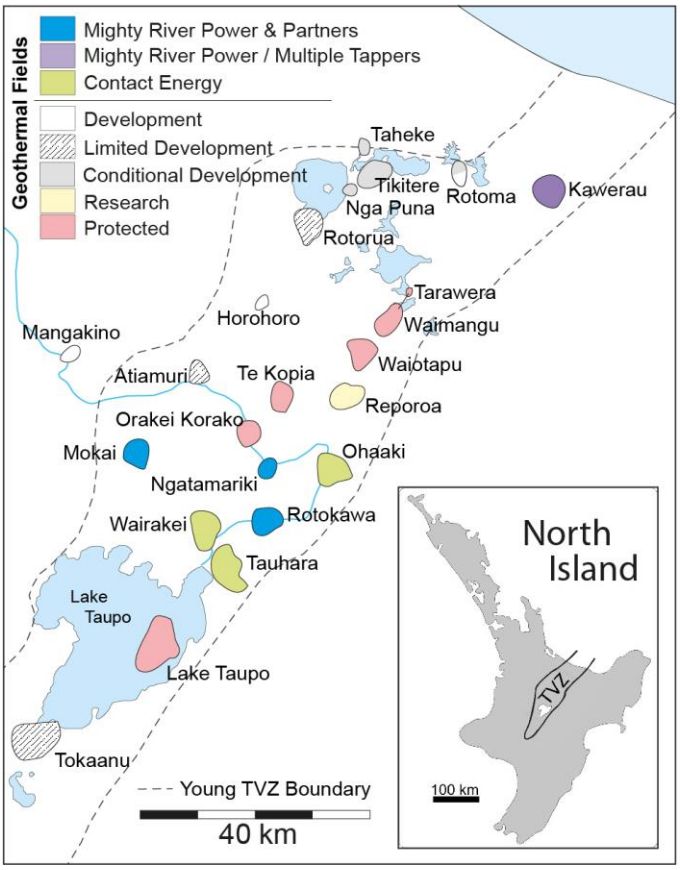


Figure 2: Geothermal fields within the Taupo Volcanic Zone (Wilson et al., 1995), shown by their resistivity boundaries (Bibby et al., 1995)

3.1 Kawerau Development - Test Plant and Early Kawerau Operations

The Kawerau Geothermal Field was the first major geothermal build undertaken by Mighty River Power. A number of wells were drilled, with two of these wells being identified for future production being capable collectively of producing at least 30 MWe. Geoscience studies were conducted and both a binary and a dual-flash development were considered. For the flash plant, the planned silica management option was pH modification via acid addition. For the binary plant, silica management included condensate addition with and without acid dosing.

A test plant was designed and constructed to test both potential plant designs (Brown & Rock, 2010). Both design types were built into the test plant and tested, but for the purpose of this paper only the flash plant will be discussed in any detail as this was the selected development (Gray, 2010). A number of findings were made from the test plant process:

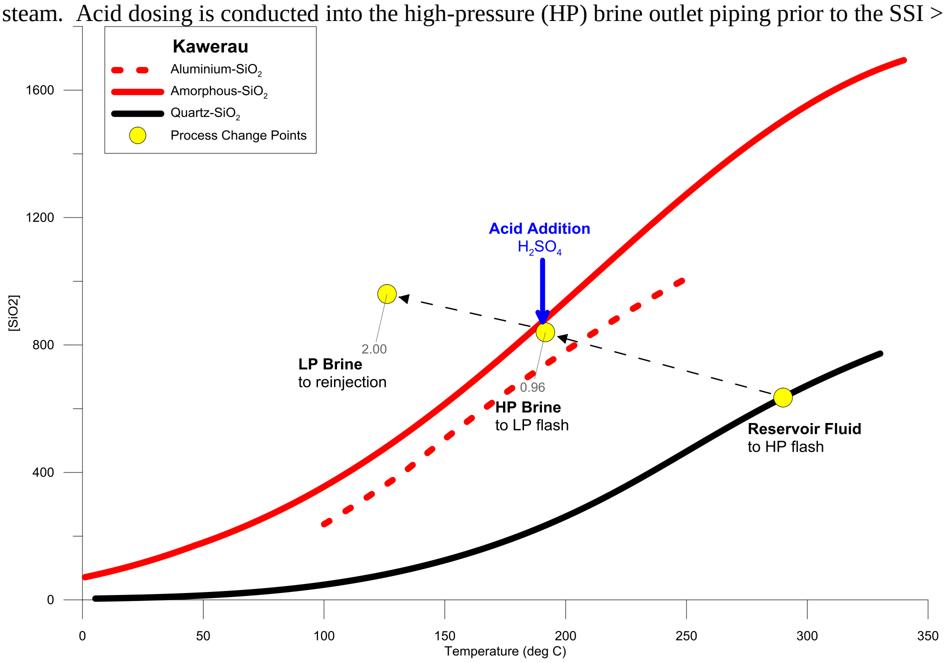
1) pH modification with sulfuric acid addition to a pH_{25} of 5.0 was sufficient to inhibit silica polymerization within the plant and simulated reinjection pipework if the second flash temperature remains above 120˚C
2) Reducing the pH upstream of a separator before fluid passed an SSI of 1.0 was required to inhibit silica polymerization, rather than dosing directly within a separator, and a separator provides good mixing for subsequent pH measurement downstream

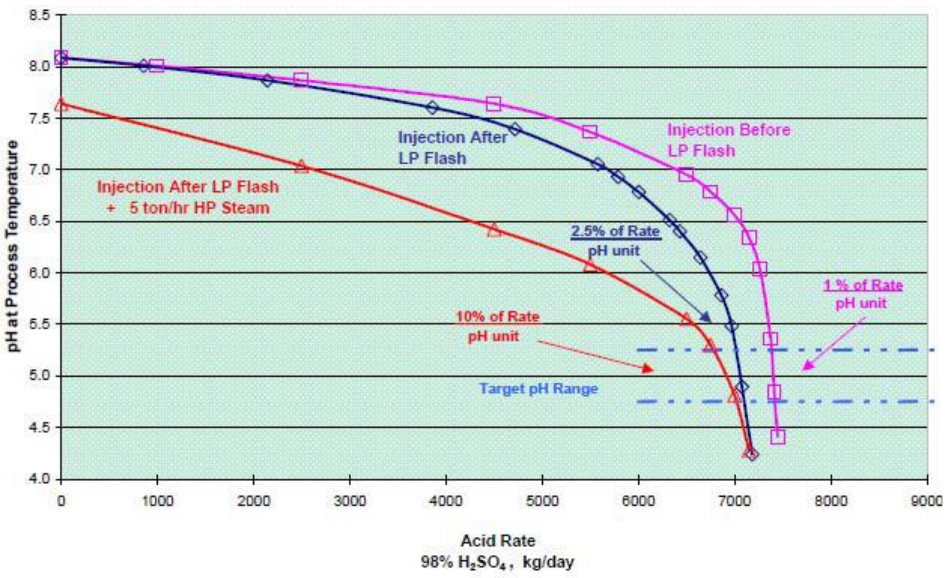
3) Glass pH electrodes tended to lose responsiveness quite rapidly and solid state electrodes proved much better
4) Temperature changes in bulk 98% sulfuric acid led to density changes, changing pumped rates
5) For good pH control the acid needs to be diluted before addition to the main flow
6) For acid injection there were material compatibility challenges, especially at a temperature of ~190˚C
7) Antimony and arsenic deposition occurred, with elemental antimony depositing when hydrogen sulfide is at low concentrations
8) Commercial silica anti-scalants that were tested did not work, generally because they acted as dispersants rather than preventing the formation of colloids
9) Corrosion was within acceptable levels with a pH_{25} of 5.0 for reinjection pipework constructed of carbon steel

Two major limitations identified in the test plant were (1) the inability to match the exact physical conditions (such as flow and velocity) within a pipe, especially in two-phase flow following the downstream flash after acid-dosing, and (2) the complexity in testing the fluid-rock interactions that may occur once the fluid is injected into reservoir formation.

Following the completion of the test plant, development specifications were updated and construction of a dual-flash power station commenced, alongside further drilling for both production and injection and more detailed steam-field design. This development was Mighty River Power’s first experience with a flash plant and its first experience with utilizing acid dosing for silica control. Making use of pH modification to exceed a SSI of 1.0 allowed an extra 17-18% gross electricity generation in the plant design. The power plant was designed with a direct-contact condenser, therefore mixing condensate back with the brine was not recommended due to the presence of oxygen.

A schematic of the brine system that was constructed is provided in Figure 3. High Pressure (HP) separation occurs at approximately 12.4 bar(g) and Low Pressure (LP) separation occurs at approximately 1.4 bar(g). Two stages of reinjection pumps are available; however a bypass option is present on the second stage of pumping, allowing for a reduction in parasitic load if these pumps are not required. The installation of safety dump valves enables the diversion of brine to ponds while the plant is started up and pH modification is under control before initiation of reinjection. Two LP separators were constructed, which allowed smaller vessels to be constructed than would otherwise be required to reduce steam velocities and subsequent mechanical carryover of brine into the steam. Acid dosing is conducted into the high-pressure (HP) brine outlet piping prior to the SSI >1.0 ((A)





(B)

Figure 4A) as a single stage based off HP brine flow, with pH measurement used to trim the flow ratio controller. Acid dosing can be conducted in more than one stage (Jost and Gallup, 1985; Mroczek et al., 2010) which can be advantageous in mitigating corrosion while still reducing the pH sufficiently to inhibit colloid formation at that particular plant location before further acid is added. However multiple acid dosing locations requires more control logic complexity and more acid injection facilities. MRP designed in single point acid dosing. (A)

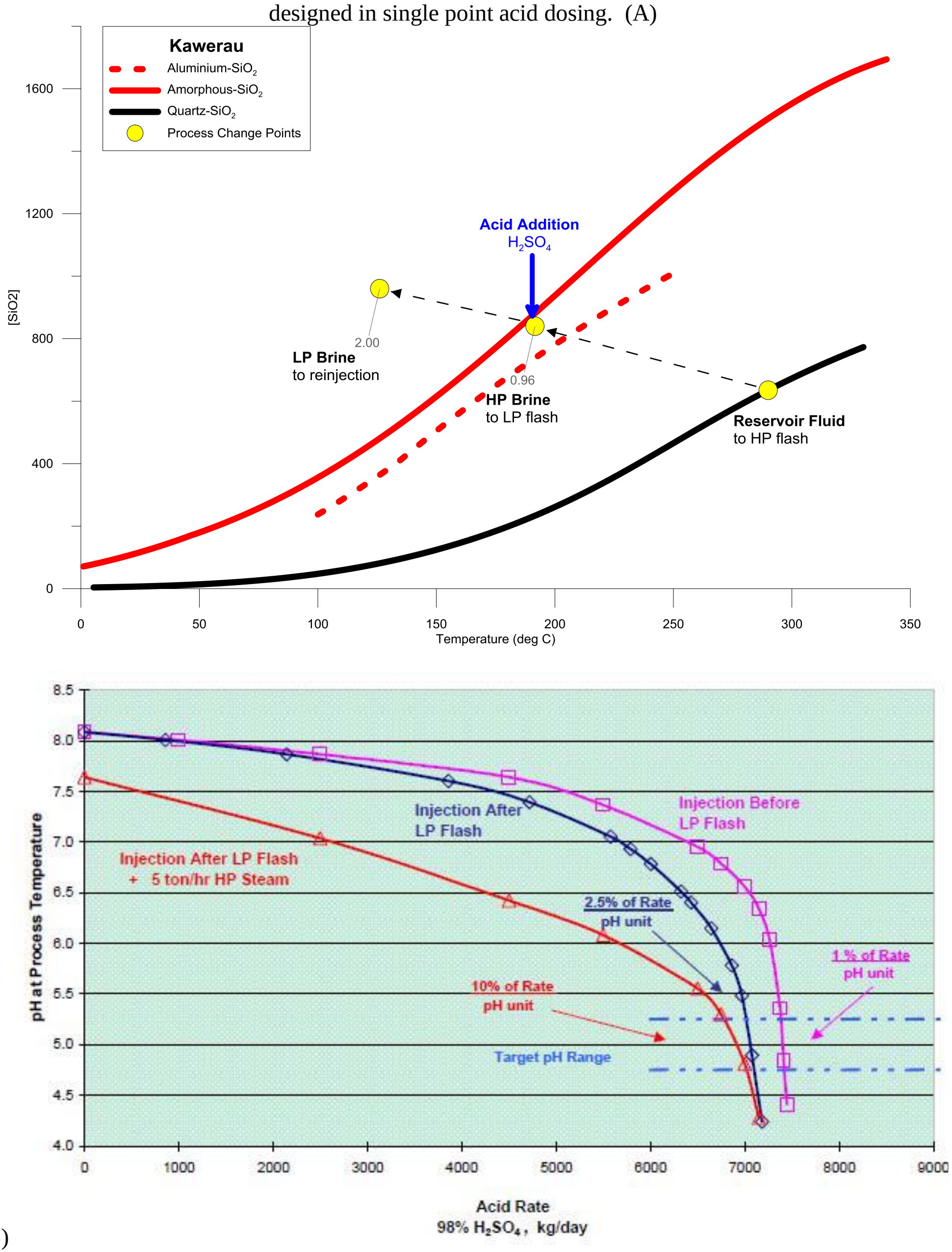


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Figure 4A shows the process change impacts on silica concentration relative to fluid temperature, with solubility curves shown for quartz, pure amorphous silica and aluminum-rich amorphous silica.

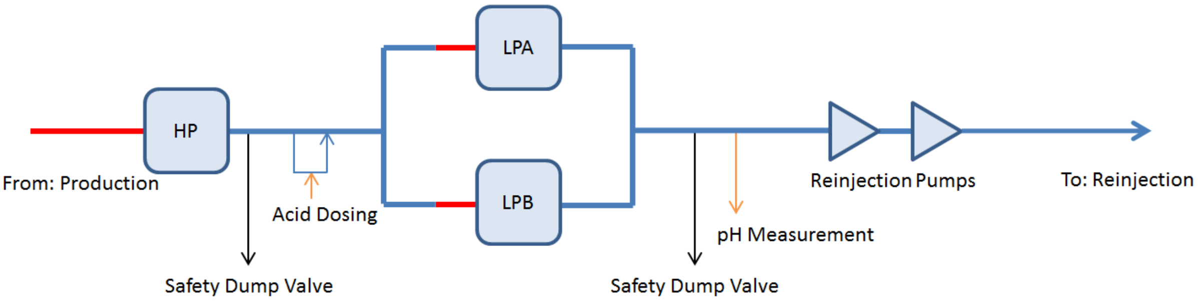
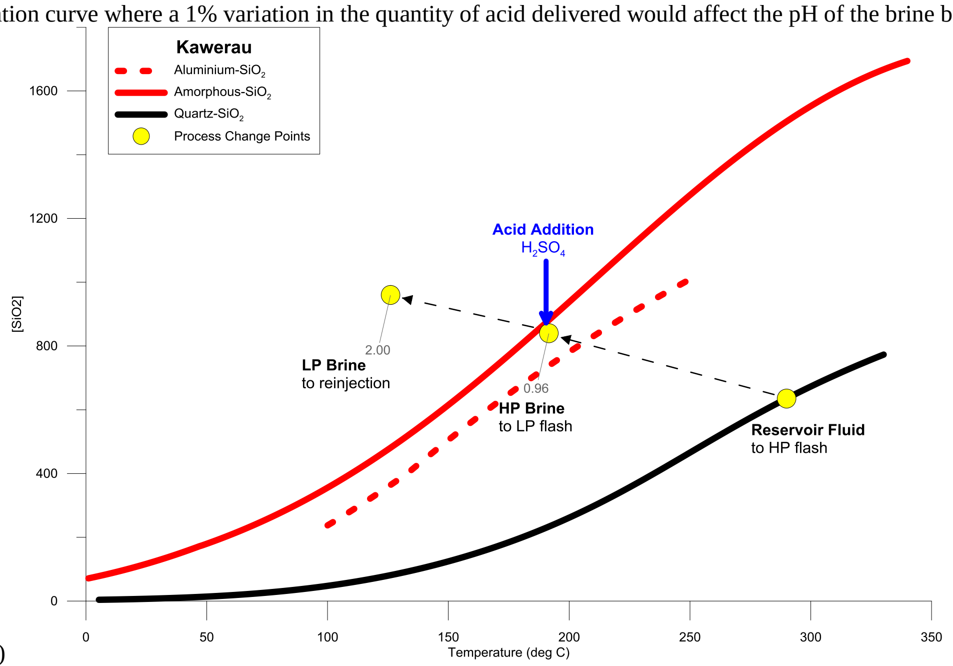
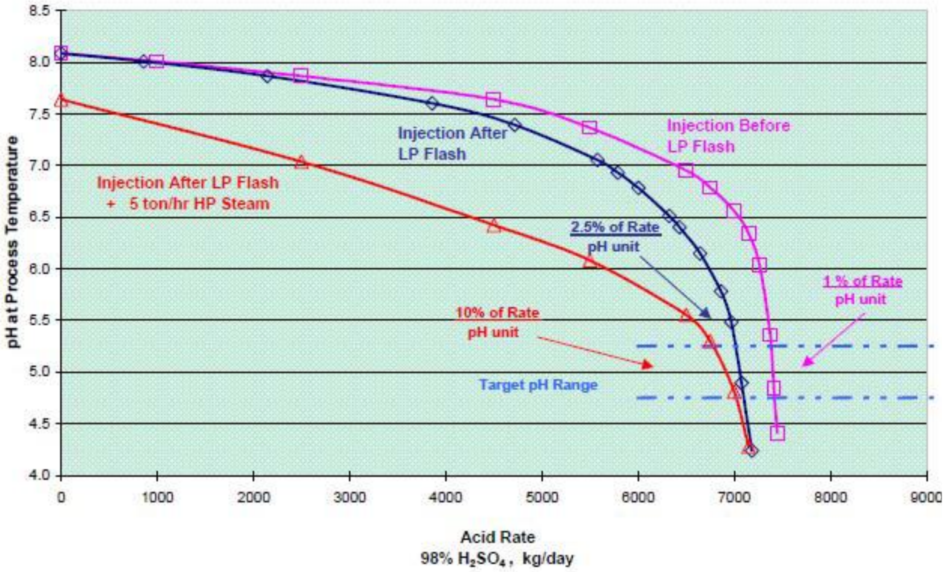


Figure 3: Kawerau Geothermal Power Station brine process schematic. Red indicates areas of two-phase fluid and blue indicates main brine flow. Acid dosing areas are shown in orange.

Commissioning commenced at Kawerau in early 2008 with six production wells feeding the power station, three of which had previously been tested with chemistry sampling and analysis conducted. During the early stages of commissioning pH modification instrumentation and hardware proved to be a complex operation. Conducting pH modification upstream of the LP separators resulted in a steep titration curve where a 1% variation in the quantity of acid delivered would affect the pH of the brine by a whole pH unit ((A)





(B)

Figure 4B), creating complexity in the method of pH control within the brine.

The elevated temperature at which acid was added (around 190˚C) resulted in rapid corrosion of the Hastelloy C-276 quill (Figure 5), necessitating alternative materials testing and a redundant injection point being installed. With new wells coming online, the acid dosing requirements to achieve a pH set-point was much higher than initially tested and modeled. Larger acid dosing pumps were required to meet the acid dosing requirements (5 - 6.5 L/min) and subsequently the cost of pH modification was higher than anticipated. Dilution of 98% sulfuric acid is exothermic and as the HP brine was near saturation, this led to flashing within the acid dosing pre-dilution and main flow leading to further material compatibility challenges. The use of hotwell condensate was tried as an alternative to using HP brine as pre-dilution for the concentrated acid. While this meant there was a significant temperature buffer before the diluted acid flashed, it resulted in the introduction of aerated fluid. Pre-diluted acid (an oxidant) mixed with the reducing brine environment lead to high levels of corrosion in the downstream pipework, requiring a change back to using HP brine for dilution.

Corrosion of the LP two-phase pipework was significant in localized areas, in particular on the outside of 90˚ bends and on the expander cones downstream of the control valve where flashing occurred. The rate of corrosion appeared worse on one LP two-phase leg than the other. To help mitigate the corrosion, a mix of redesign and weld overlays were used (Figure 6). Inconel 625 weld overlays were utilized and other weld overlays and metal sprays were trialed. After a period of use cone angles were modified and some of the redesigned tees were swapped back to bends at the request of the pressure-vessel inspector.

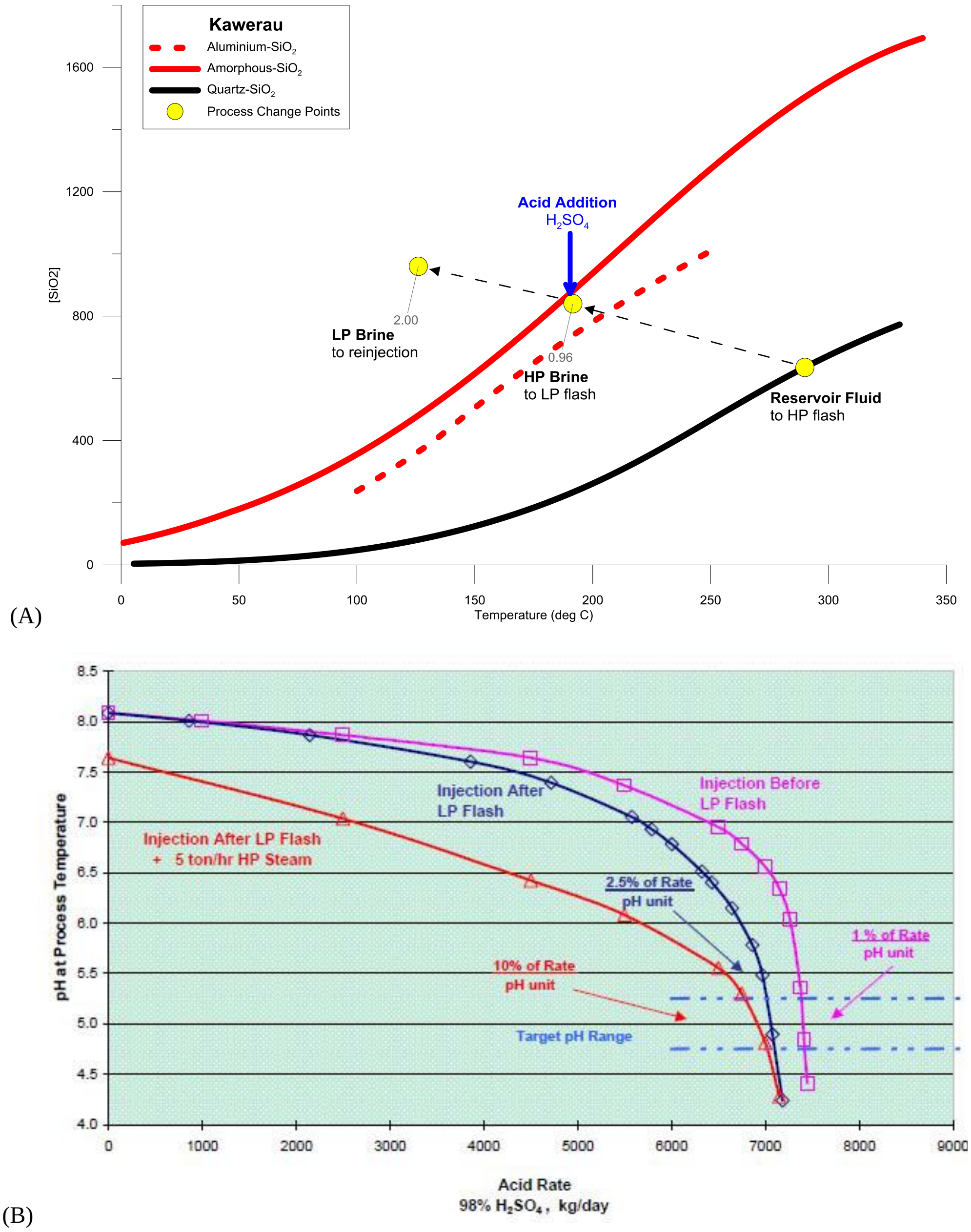


Figure 4: [A] Kawerau process change shown on a silica concentration vs. temperature plot with various solubility trends. SSI values are provided relative to pure amorphous silica solubility (continuous red line - modified from Fournier & Marshall, 1983 and Fournier, 1989). Quartz solubility is shown as a continuous black line (Fournier & Potter, 1982). Aluminum-rich amorphous silica solubility is shown for 100˚C-250˚C (modified from Gallup, 1998 and Bjorke et al. 2012). [B] The titration curve upon plant startup with various pH modification processes shown.

Injectivity was monitored as a function of Injectivity Index (II - measured as t/h/bar). The II declined around 50% during the first year of operation, apparently due to silica scaling in the well bores. After investigations with downhole camera and PTS runs, a well acidification program (Lim et al., 2011) was attempted to recover the injectivity in two wells. While some injectivity was recovered, decline continued within a month to the previous injectivity. Two additional injection wells were subsequently drilled, following the casing failure in one injection well unrelated to silica and continued injectivity decline in the other wells.

Kawerau features abundant calcite as an alteration mineral within the reservoir, therefore one potential mechanism of decline is through pH increasing near wellbore through the formation of bicarbonate. This neutralization is likely to reduce the induction time before silica polymerization occurs. The equation of acid reaction with calcite is given as:

$$H^+ + CaCO_3 \rightarrow Ca^{2+} + HCO_3^-$$

Section 2.3 below goes into detail on later operational improvements at Kawerau.

Figure 5: Before and after service photos of an H-276C injection quill at the Kawerau Geothermal Power Station where the quill is exposed to acid concentrations of 1-2% and temperatures of approximately 190˚C, with some flashing occurring due to the exothermic mixing of acid with water.

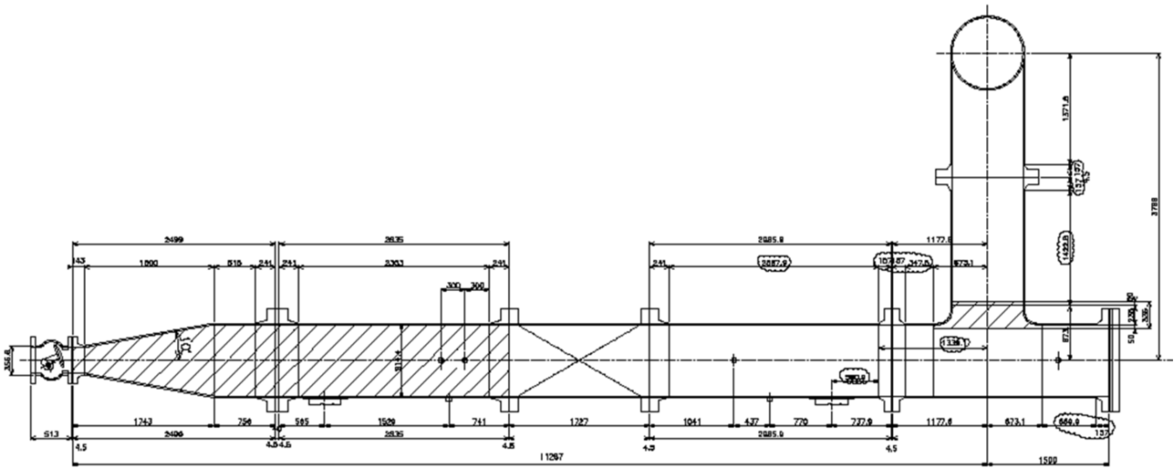


Figure 6: Modified LP two-phase pipework, replacing a 90˚ bend with a flanged tee. Shaded areas indicate where weld overlays were initially applied.

2.2 Nga Awa Purua

While construction of Kawerau was being undertaken, testing of the Rotokawa field and proposed plant designs were being undertaken. As part of the contract for the Kawerau project, an option with the turbine supplier was negotiated to construct another flash plant, named Nga Awa Purua (NAP) for the Rotokawa field. Due to higher reservoir temperatures and expected discharge enthalpy at Rotokawa, this plant had a higher requirement for the HP separator pressure to remain under-saturated with respect to amorphous silica.

The design consideration for this plant was focused on maximizing the plant efficiency, standardizing plant and equipment where possible, incorporating lessons from the Kawerau project and improving the plant layout. The decision to go to a triple-flash design allowed for an additional 6 MWe of generation compared to a dual-flash for the same geothermal fluid take (Gray, 2010). Test plant design and construction was undertaken with fluid fed from three wells feeding the existing Rotokawa binary geothermal power station. Testing was only conducted on a triple-flash design with pH modification. Key outcomes were to test various LP separator pressures and various pH set-points.

With the increased HP separator temperature, material challenges were exacerbated around acid dosing. The plant design took forward lessons around materials from the Kawerau project given the 30˚C temperature increase in the HP brine. Two 100% acid injection systems, including pre-dilution systems, were included in the NAP design. A simplified schematic is shown in Figure 7. High Pressure separation occurs at approximately 24 bar(g), Intermediate Pressure at 8.5 bar(g) and Low Pressure separation occurs at approximately 1.7 bar(g). Two stages of reinjection pumps are available; however a bypass option is present on the second stage of pumping, allowing for a reduction in parasitic load if these pumps are not required. After testing, a pH set-point of 5.0 in the reinjection brine was determined to be optimal along with a LP separator pressure of 1.7 bar(g). To achieve a pH of 5.0 in the reinjection brine, the pH is considerably lower in the HP brine when dosed. Changes in silica concentrations across the various flash points and the subsequent SSI values are shown in Figure 8.

A significant drilling campaign commenced and the NAP project was completed ahead of schedule. Acid dosing requirements were within the ranges of those predicted and modeled with acid use at 0.8 - 1.5 L/min. Section 2.3 below goes into detail on later operational improvements at NAP.

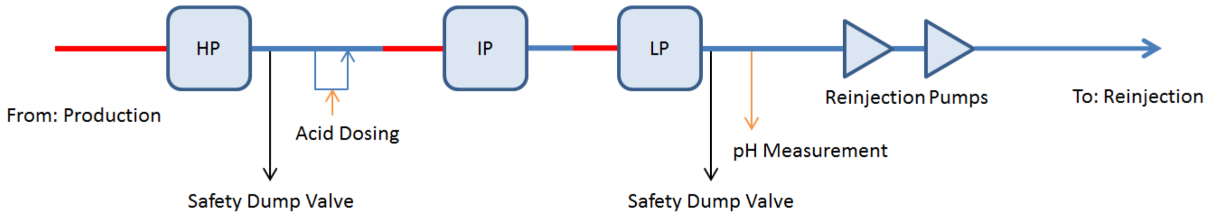
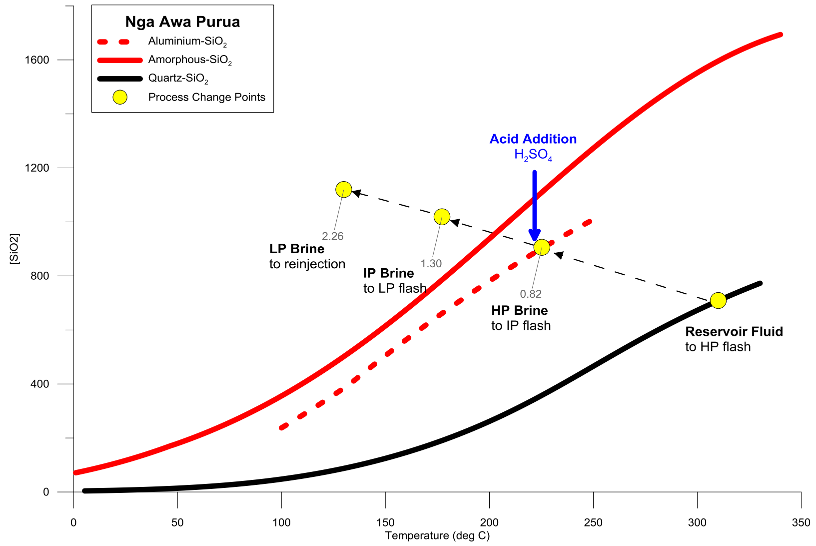


Figure 7: NAP Geothermal Power Station brine process schematic. Red indicates areas of two-phase fluid and blue indicates main brine flow. Acid dosing areas are shown in orange.



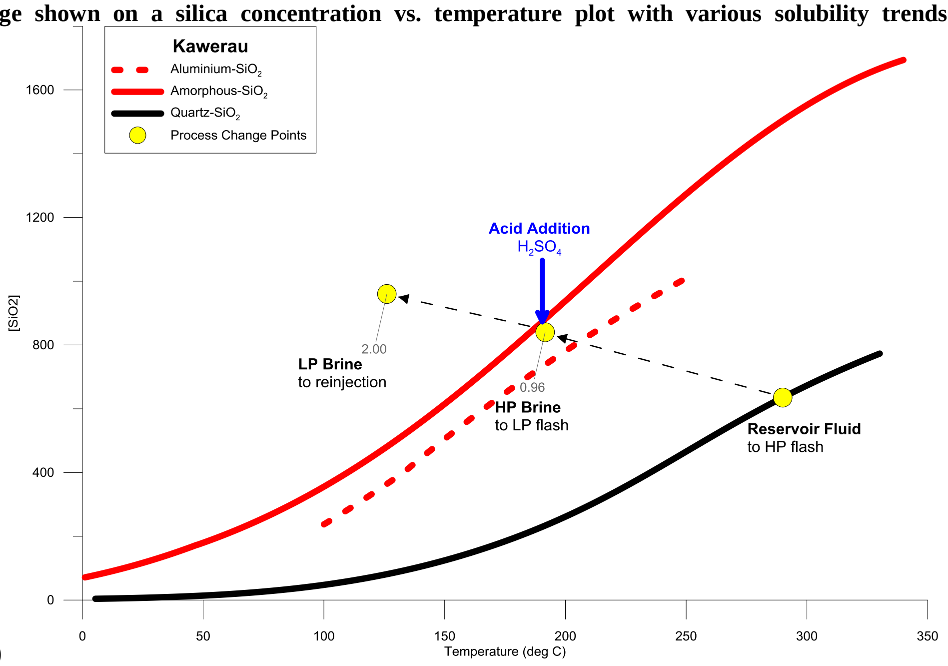
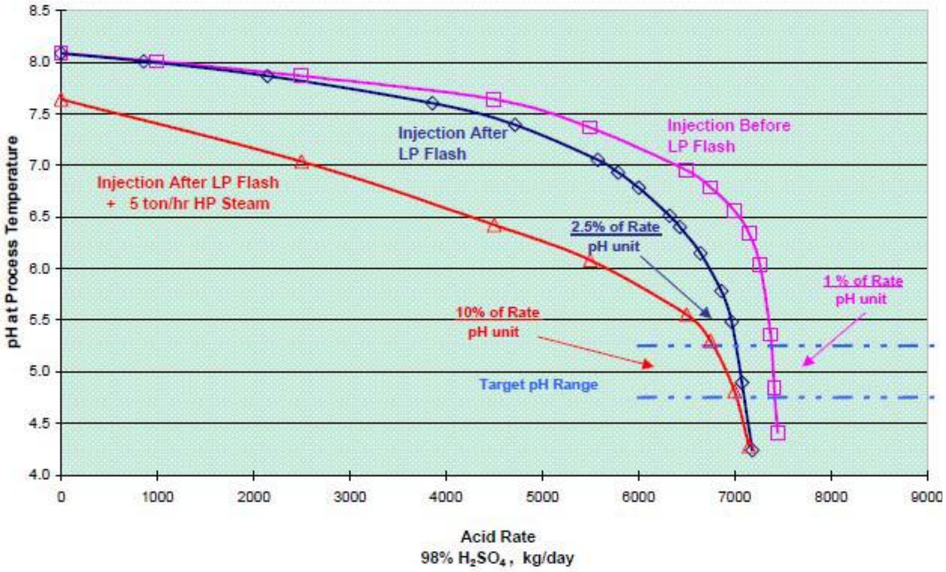


Figure 8: NAP process change shown on a silica concentration vs. temperature plot with various solubility trends. Solubility trends are as per (A)



(B)

Figure 4A.

2.3 Continued Kawerau Operation and Early NAP Operation

With the continued declines in injectivity at Kawerau, a project was initiated to investigate the cause and possible modifications to both acid systems. Some of the initial findings from this project were:

1) Once an injection well dropped below the saturation pressure at the well head, the injectivity index evolution could no longer be monitored without downhole pressure tubing, i.e. a fluid level in the well was required to monitor injectivity change
2) The glass pH meters at Kawerau exhibited upward drift by up to 0.5 of a pH unit, which meant that the time before polymerization would occur was reduced, while at NAP no drift was observed
3) Historically, injectivity would make step-changes downwards on station and on brine reinjection start-up and shut-down, possibly suggesting operational causes
4) Flow was not stable in the Kawerau HP brine, but was stable at NAP
5) pH was not stable in the HP brine at Kawerau
6) Localized corrosion on bends in the 2-phase pipework after acid addition was significant, more so at Kawerau than NAP
7) Localized corrosion on bends was higher on one leg of the LP than the other at Kawerau

An immediate action at Kawerau was to increase the manual calibration frequency of the glass pH meters, while design and procurement of a new pH measurement system could be conducted. The plant was operated for a period of time after changes in injectivity to allow correlation to a stable pH condition. Another operational change was the installation of brine diversion ponds at wellheads to allow for the dumping of stagnant brine from the pipeline due to a process upset or outage. Once pH was stabilized at the power station, flow would be routed through the pipeline to the wellhead ponds until the temperature stabilized before turning it into the injection well. An iron monitoring program (indicator of corrosion) was initiated, with profiling of the plant process at regular intervals alongside regular thickness checks using non-destructive testing (NDT).

Both stages of reinjection pumps were utilized at both plants, with injection pressures up to 16 bar(g). The ability to have the pressure high reduced the total number of injection wells required by increasing the total injection flows down each well. As pH modification only affected the kinetics of silica polymerization, pumping also allowed residence time in the pipeline and wells to be reduced. Injection well configuration was changed at Kawerau and at NAP, pumping condensate into previous brine injection wells to attempt to recover some injectivity, when spare well capacity allowed. To enable injectivity monitoring even when a well is on vacuum, downhole pressure monitor tubing was installed in some injection wells intended to be used at lower well head pressures to monitor the evolution of liquid level within the wells. As injectivity index is susceptible to change with changes in reservoir pressure, correcting for reservoir pressure increase in the injection area is also important. A further improvement to this technique is a downhole distributed temperature sensor (measures the temperature profile of the well) to enable monitoring of specific permeable zones, however this has yet to be tried on an injection well and has temperature constraints. Brine injection at NAP was successful enough to shift to a single injection well to reduce residence times.

While focus was applied on refining the understanding of the pH modification process, investigations and feasibility studies were started for looking at a CRC plant. These studies identified that the construction of a CRC plant at Kawerau would cost in the vicinity of NZ$45M and increase operator requirements by one full-time equivalent. The use of a CRC plant would also result in cooler injectate back to the reservoir, posing risks for potential reservoir cooling, as well as disposal of the silica removed.

The use of a continuous brine monitoring tracer flow testing (CBM-TFT) along with an ISFET data-logging pH meter established that at Kawerau the acid mixing was insufficient and there was an imbalance of acid toward one leg after the split of HP brine. In addition, HP brine flow rates that fed through to the distributed control system (DCS) had increased noise due to the irregular flashing of the brine downstream of the orifice plate due to acid addition and a subsequent pressure increase, shown in Figure 9A. To help reduce the level of noise, a moving average was used in the control system for brine flow ratio control used to calculate acid flow requirements; investigations into the control logic and hardware were also made. At NAP, HP brine flow was comparatively stable, as was the acid delivery flows and the subsequent pH. Due to the lower levels of acid addition required at NAP compared to Kawerau, no additional flashing due to the exothermic dilution of acid occurred. Localized corrosion in two-phase pipework downstream of acid dosing was much lower at NAP comparatively, with lower acid requirements and also better acid mixing with the use of a 'vane' mixer instead of a 'fin' mixer.

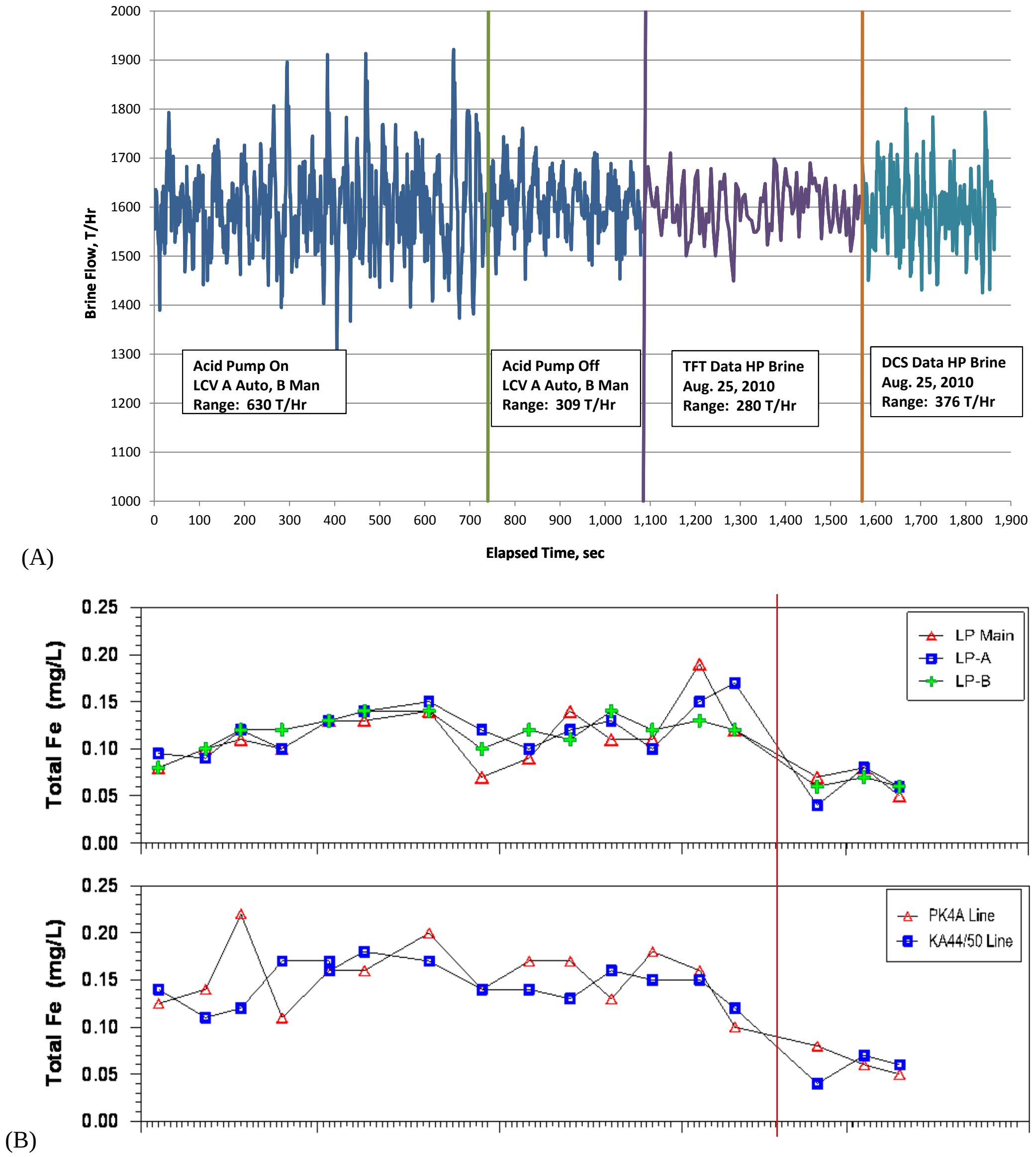


Figure 9: [A] HP brine flow in various conditions. The left hand two sections represent control valve commissioning, showing a reducing HP brine flow noise. The right hand two sections represent the same flow condition, with the purple section measured using CBM-TFT and the turquoise measured from an orifice plate and fed through to the DCS. [B] Iron monitoring with time at a reduced pH, the top graph showing low pressure brine out of each separator and the combined while the bottom graph shows the total iron levels at injection. The vertical red line indicates when carbon steel bends were replaced with a higher grade alloy.

Continued injectivity declines at Kawerau meant that investigations began into decreasing the pH. Side-stream testing of corrosion was conducted with corrosometers, along with modeling of stable corrosion product species on the pipe, as a baseline prior to any reduction in pH at the plant. Once a reduction took place, monitoring of injectivity continued along with iron monitoring and NDT.

In **Error! Reference source not found.**A a simplified diagram shows relative scaling and corrosion, indicating that as pH is reduced, scaling reduces but at the expense of an increasing corrosion rate. With the reduction in pH, specific areas of the plant can be changed to higher grade materials to reduce iron solubility and therefore the corrosion rate. In Figure10A a reduction in pH from *a* to *b* and a corrosion replacement with a higher grade alloy reduces the corrosion from *a'* to *b'*.

The presence of metal ions such as Fe^{3+} and Al^{3+} can reduce the solubility of amorphous silica (Gallup, 1998; Bjorke et al., 2012), therefore the oversaturation of silica can be higher and the effective scaling rate for a particular pH can be higher. In Figure10B a pH at *a* shows the scaling rate is higher for aluminum-rich amorphous silica (*a'* from the dashed blue line) compared to pure amorphous silica (*b'* from the solid blue line). To achieve an equivalent level of scaling for amorphous silica, pH has to be reduced from *a* to *b*, but this results in an increase in the corrosion rate from *b'* to *a'* for carbon steel. Aluminum in reservoir fluid at Kawerau is on the order of 1-1.5 ppm, while at Rotokawa it is on the order of 0.5-1.5 ppm. Scale analysis using XRD and XRF from samples collected during station shuts shows that deposits are generally aluminum-rich amorphous silica, rather than pure amorphous silica, in both plants.

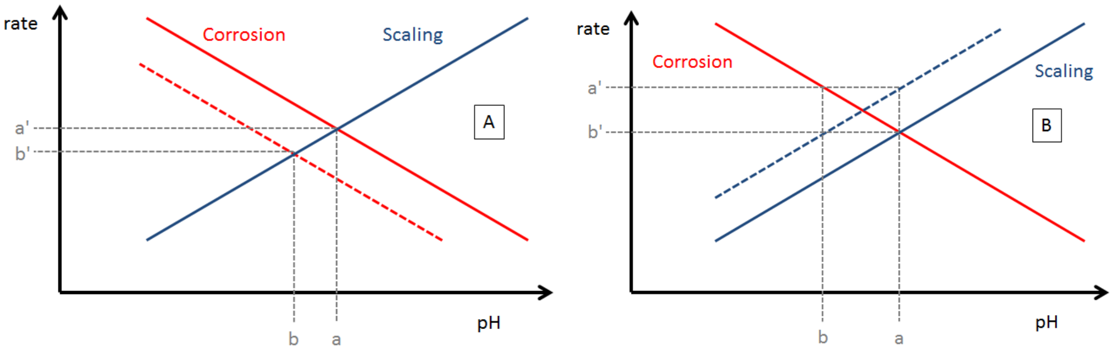


Figure 10: Simplified diagrams of corrosion rate and scaling rate against pH. [A] shows a relative rate of scaling of amorphous silica (solid blue) relative to a corrosion rate of carbon steel (solid red) and a corrosion rate of an alloy (dashed red). [B] shows a relative rate of scaling of amorphous silica (solid blue) and a scaling of aluminum-rich amorphous silica (dashed blue) relative to a corrosion rate of carbon steel (solid red)

Injectivity declines were still at a level considered unacceptable after a period of time, so the pH set-point was once again reduced further. Corrosion rates within the LP two-phase pipework increased to the point that carbon steel bends were wearing through in a period of approximately 3 months, requiring patch weld repairs while the manufacture of flanged alloy bends were being completed. Once the alloy bends were installed, the level of iron transport downstream was reduced as indicated by Figure 9B. A new pH measurement system with a fast-response sample conditioning system and ISFET pH meters was installed (Addison et al., 2013) and run alongside the original system glass probe pH system during commissioning. Running in parallel showed that the real pH within the brine was often significantly different (both high and low) during station startup and process upsets, helping explain observations of step-changes downwards in injectivity during plant process upsets and startup conditions. A concern with moving from glass pH probes to ISFET pH probes was that there may be an offset between the two types of probes. No offset was observed and the much greater resolution and faster response compared to glass probes is shown in Figure 11A.

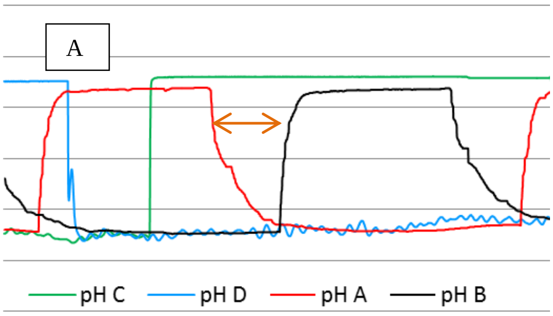


Figure 11: [A] ISFET pH meters (C&D) shown against glass pH meters (A&B). The orange arrow indicates a time period of 5 minutes. Each pH probe cycles between analyzing geothermal brine (low values) and being washed (high values). Responsiveness to reading brine pH values is almost instantaneous with ISFET probes, however takes over 5-minutes for glass probes.

Investigations were made into two-stage acid injection, whereby less acid is added to the HP brine and an acid boost provided in the injection brine. However as part of a review of costs, it was concluded that it was better to upgrade the materials in the LP two-phase pipework and to metal spray within the separators. As part of the material upgrade for the LP two-phase pipework, the HP brine pipework was redesigned to allow for better acid mixing and the distance between the orifice plate flow meter and the acid dosing injection location was increased. New control valves were installed along with a faster controller in the DCS. While these modifications assisted brine flow stability slightly, they didn't lead to any significant change. Investigations continue into looking at options to reduce noise in the HP brine flow readings through use of a non-aerated dilutant or cooled brine.

Following 8 months of injection of pH modified brine, injection was moved to another well 1 km away. One year after injection had been moved, the former injection well was flowed, shut in for a further 6 months and flowed once again. The injected brine contained 1050-1150 ppm silica (SSI ≥2.3). During the flow testing, reservoir-corrected silica values were between 900-1050 ppm indicating much of the injection fluid remained near the well and would have required a separation pressure of 33 bar(g) to stay below a SSI of 1.0. Total silica and monomeric silica testing matched at a production pressure of 23 bar(g), indicating amorphous silica had either been re-dissolved or never polymerized. The implications of this production test is that pH modified brine may not re-equilibrate to quartz within a short-medium timeframe within the reservoir or is establishing a localized equilibrium with amorphous silica.

With acid dosing there are significant questions still unanswered around downhole understanding. Regular well geochemistry data collection as part of a comprehensive reservoir monitoring program allows for tracking of reservoir silica with time. In flash plants that feature evaporative cooling, through this process silica concentrations injected are higher than what is produced. It is possible for the silica concentrations to be higher in the production fluids with time if there are returns of fluid not in equilibrium with quartz. Potential mechanisms to manage this include increasing the HP separator pressure, increasing the levels of acid dosing, dosing acid further upstream or looking at alternative silica management options. It is important to design the power plant with some level of tolerance to allow for changes in reservoir response.

2.3 Ngatamariki

The Ngatamariki project was MRP's first true greenfield development. Four wells were drilled by the Government during initial exploration of a number of geothermal fields in the 1980's, with two of these wells flowed and sampled. Three more wells were drilled by MRP, all flowed and sampled. For this project a station with a high level of injection was selected as being most appropriate for the reservoir. Therefore two options existed – the use of a binary plant or the use of a flash plant with either injection makeup or an alternative source of cooling.

A desktop review was conducted on multiple designs, which were narrowed down to two main options for construction – either a dual-flash development, similar to Kawerau, or a binary. For the binary development multiple variations existed for where to add condensate back to the brine. A test plant was designed and constructed with the ability to test both a flash plant and a binary plant with multiple configurations, with and without acid dosing. After a testing program, it was concluded that condensate would be added to the brine prior to the preheater, making use of condensate to both dilute the brine and also provide a natural form of pH modification prior to these fluids exceeding an SSI of 1.0. During the detailed design, a brine superheater was added as a design optimization to extract more energy through the superheating of the N-pentane. A simplified schematic is shown in Figure 12 and silica concentrations vs. temperature are shown in Figure 13.

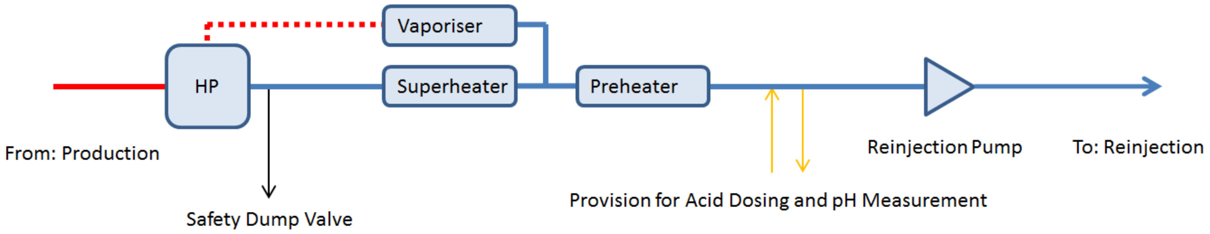


Figure 12: Ngatamariki process flow. Solid red indicates two-phase flow. Dashed red represents steam. Solid blue represents brine, condensate and brine+condensate mix. Provision for Acid Dosing and pH Measurement was included in design.

Test plant results indicated that the natural pH of 5.6 was sufficient to inhibit silica polymerization, but that by reducing the pH prior to the preheater antimony sulfides and arsenic sulfides would deposit and cleaning would be required periodically. The exit temperature from the preheater was also optimized from the test plant program at 90˚C, providing a final SSI of ~1.9. The installation of acid dosing either upstream or downstream of the preheater would have likely exacerbated the antimony and arsenic scaling risk due to lower solubility at lower temperatures, therefore this was removed as a plant design optimization. However acid dosing provisions were made in the plant to allow a fast installation of an acid dosing system if required. After one year of operation the Ngatamariki injection wells have shown steady increases in injectivity due to thermal stimulation, with no signs of scaling noted.

3. CONCLUSIONS

Successful brine silica management enables the extraction of additional energy from the produced geothermal fluids. However long-term injection of this fluid can be a highly complex challenge that requires significant data, scientific conceptualization and ongoing adaptation. There are large economic rewards for managing silica risk successfully, for example an extra 17-18% of electricity generation at Kawerau.

There are many options for managing silica, with MRP making use of pH modification through acid addition or steam condensate addition, as well as dilution with condensate. Controlling silica polymerization is complex due to the high number of variables that may lead to polymerization occurring and subsequent deposition. While standard designs to manage silica can be utilized in places, the overall strategy of silica management needs to be customized based on the reservoir conditions and the subsequent plant design. It is important to design up-front for silica management, as it is cheaper than after design and construction has been completed. Operating plants across multiple geothermal fields allows for learning to be subsequently applied across other generating assets where appropriate.

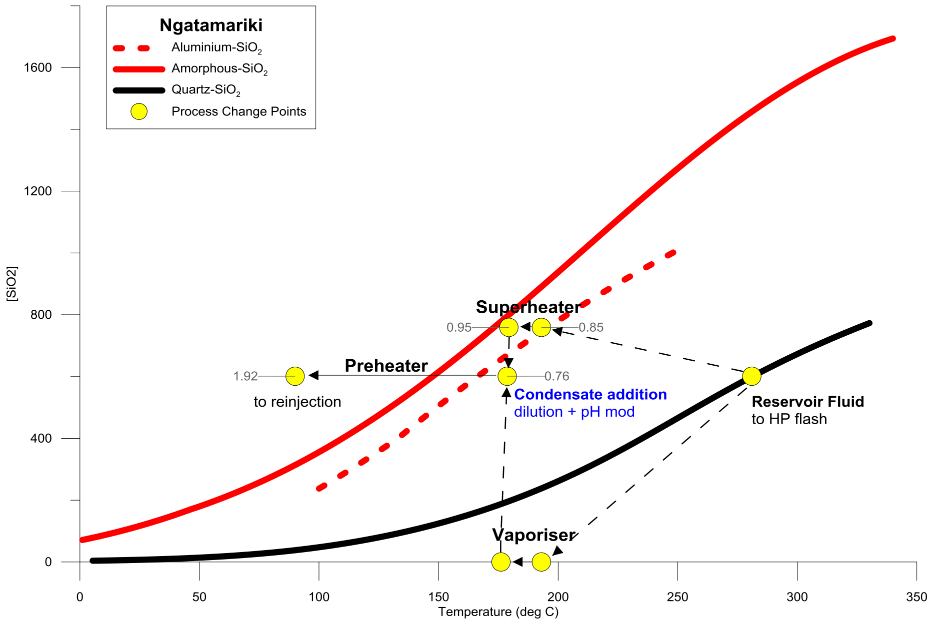
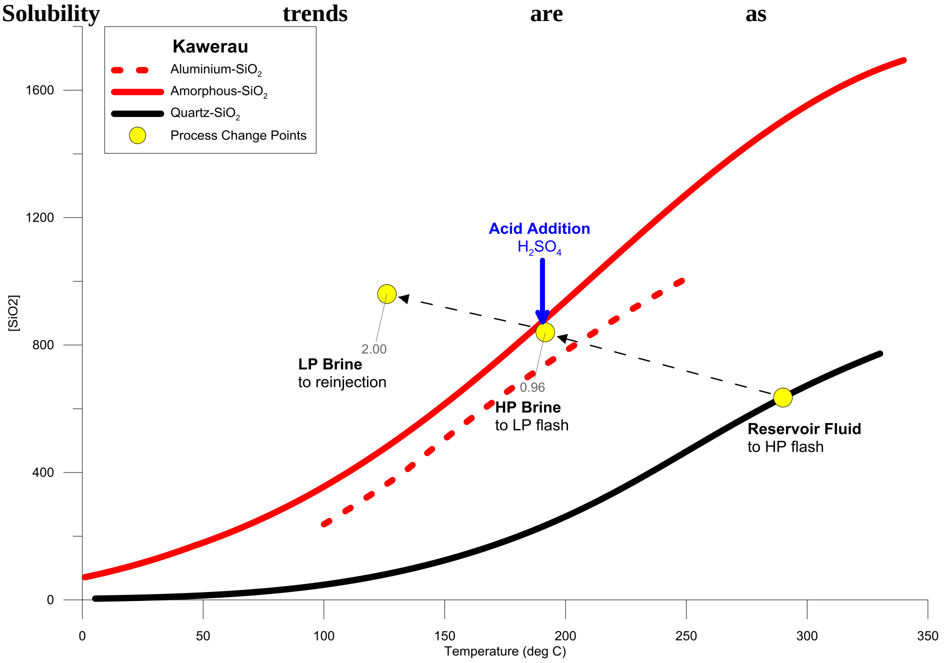
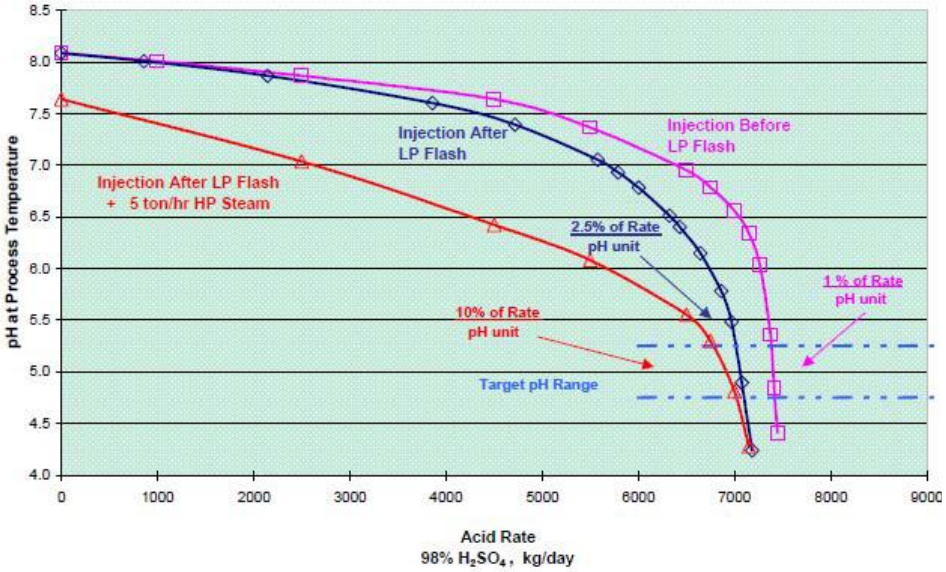


Figure 13: Ngatamariki process change shown on a silica concentration vs. temperature plot with various solubility trends. Solubility trends are as per (A)





(B)

Figure 4A.

With pH modification one of the main challenges that eventuate is that of corrosion. Applying higher specification materials throughout the process has the potential to make development uneconomic, therefore applying correct choices of materials in targeted areas especially around acid dosing helps to balance both silica polymerization and corrosion risk.

As a company, MRP continues to develop its knowledge and understanding of silica management options, in particular for pH modification. The operational knowledge gained feeds back into MRP's development strategy and employer's requirements for future power plant developments and existing operational plant modifications, helping to assist with a reduction in risk around silica management into the future.

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