NGATAMARIKI TEST RIG

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ABSTRACT

At an early stage of the development of the Ngatamariki field, Mighty River Power designed and constructed a test rig utilising geothermal fluids from NM7 to simulate and test a variety of plant designs and conditions. Both a flash test plant and a binary test plant were constructed and tested, to help design the optimal plant for Ngatamariki. Scaling rates and elemental analysis of the deposited scale were determined for test sections located throughout the process for each trial. Additional measurements included silica polymerisation times and acid titration curves.

Three flash plant trials were conducted using a dual-flash design, all utilising acid dosing to a pH_{25} of 5.0. The low pressure (LP) separation pressure was varied between the trials, ranging from 1.7 bar(g) to 0.44 bar(g), corresponding to a temperature range between 130˚C and 110˚C. Results indicated that the scaling rate increased with a lower flash pressure and temperature, with the scaling rate being acceptable at a LP separation pressure of 1.7 barg, correlating to a silica saturation index (SSI) of 1.8–1.9. For all flash plant trials algae contamination of test pieces was observed, which is thought to be due to operational processes around the flushing and drying of pipes prior to analysis.

Three binary trials were conducted with exit temperatures tested being 95˚C, 90˚C and 85˚C. For all trials, condensate was added to the brine prior to the preheater section to reduce the pH prior to increasing the SSI to >1.0 within the preheater. In all cases both antimony sulphide and arsenic sulphide deposited within the heat exchanger, but for an exit temperature of 85˚C, significant arsenic sulphide also deposited after the preheater, limiting the design exit temperature to 90˚C. Silica deposition was insignificant in all binary trials, indicating that acid dosing is not required to control silica scaling.

1. INTRODUCTION

1.1 Ngatamariki

The Ngatamariki Geothermal Field is located ~20km northeast of Lake Taupo in the central part of the Taupo Volcanic Zone (TVZ) (Figure 1). The Ngatamariki geothermal field was first investigated in the early 1980's, with four wells drilled by the New Zealand government. In 2008 a three well step-out campaign led by Mighty River Power (MRP) commenced, confirming a sufficient resource for a ~100MWe development (Boseley *et al*., 2010). The conceptual model for the resource comprises a 260-285˚C geothermal resource.

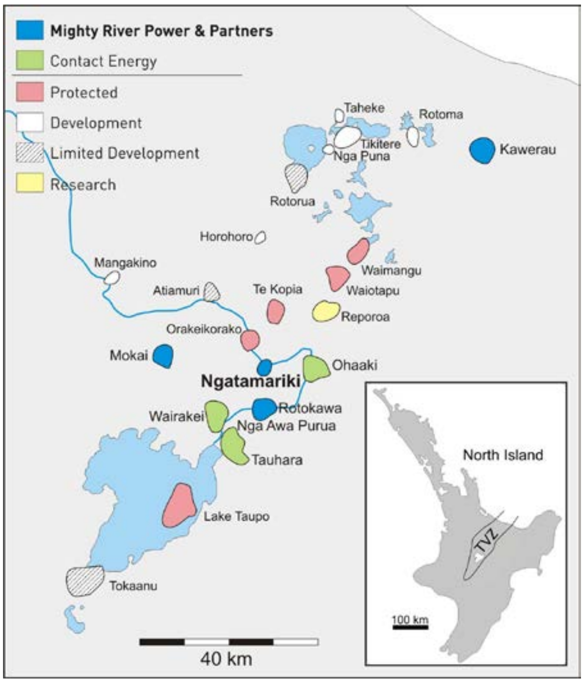

Figure 1: Location map. Ngatamariki is located in the Taupo Volcanic Zone near five developed geothermal fields

1.1.1 Current Development

At Ngatamariki Mighty River Power is currently constructing a 4-unit, 82 MWe binary plant supplied by Ormat. The development was granted consents in mid-2010 and construction began in November 2011. First generation is scheduled for early-2013 for the first 2 units and mid-2013 for the second 2 units.

1.2 Test Rig Project

At an early stage of the plant design process a test rig was designed and constructed to test different proposed power plant designs to identify the optimal plant design for Ngatamariki. The design of the test rig needed to be flexible, and be able to test designs for both flash and binary plants and any combinations thereof. Two separate test rigs were constructed, with the ability to interconnect with some minor modification if required.

The project was led by MRP and utilised a number of local contractors and consultants, assisting in the design, construction, operation and analysis of the test rig. This project structure ensured that key decisions and findings were carried from the test rig project through to the design and construction of the full-sized plant, and possible designs for the full-scale plant could be examined in the test rig. MRP had previously conducted test rig projects (Brown and Rock, 2010) as part of its developments at Kawerau and the Nga Awa Purua project on the Rotokawa field (Hoyer et al, 2010). These previous test rigs provided critical experience and knowledge, as well as providing for some vessels that were re-used for the Ngatamariki rig.

Early stage vetting of proposed power plant designs prior to assessing on the test rig ensured that only realistic designs were run on the test rig, helping to prevent the program schedule from sliding. Besides vetting for commercial parameters, lessons learnt from previous test rigs and full sized plants were applied.

Both the binary rig and flash rig featured:

- Automation via a control system, with alarms and remote alarm texting for the operators for critical alarms;
- A number of test-sections throughout the process to enable analysis of scaling after each trial;
- Temperature probes and flow meters at key stages throughout each plant;
- A hold-up vessel allowing for simulation of the retention time in reinjection lines;
- pH modification capability, via sulphuric acid addition.

The two test rigs were able to operate independently of one another, however both were fed from the same test separator for the well. If both rigs were operated concurrently they had the same initial HP flash pressure. Preference was given to the higher separation pressure that was required for the binary plant.

1.2.1 NM7

The test rig was constructed at the NM7 well site. It was felt that the well was most representative of the likely production fluids. The remote location of NM7 during the testing phase presented a number of challenges which included a lack of access to reticulated domestic water and mains electricity. As a result water was supplied to the site by truck deliveries and a portable electrical generator set was used to supply electricity to the site.

A separator, rock muffler and atmospheric silencer were already in place on site. Flashed brines from NM7 were not injected in order to eliminate any possibility of reservoir feedback and modification of the primary feed chemistry to the test rigs. Stable well operating conditions were achieved prior to and throughout the test rig operations, with a number of geochemical samplings and PTS logs conducted.

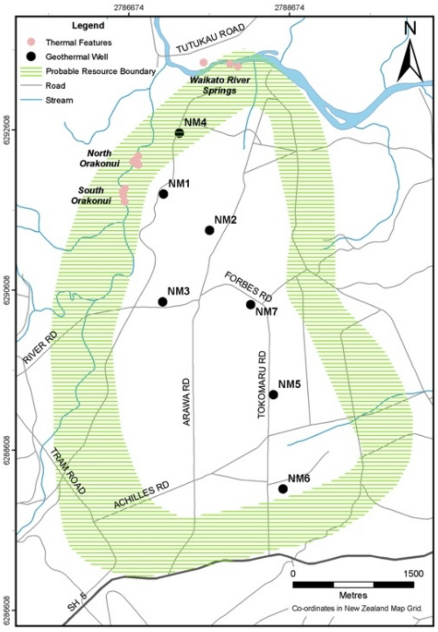

Figure 2: Ngatamariki geothermal field layout

NM7 is located in the centre of the Ngatamariki field (Figure 2). The well was completed as a big-bore well with a 13 3/8" tieback. Key chemistry constituents in reservoir concentration are shown in Table 1.

Constituent	Concentration (mg/kg)
As	2.1
Cl	957
Si	601
Sb	0.1

Table 1: Selected NM7 Chemistry Constituents

2. FLASH RIG

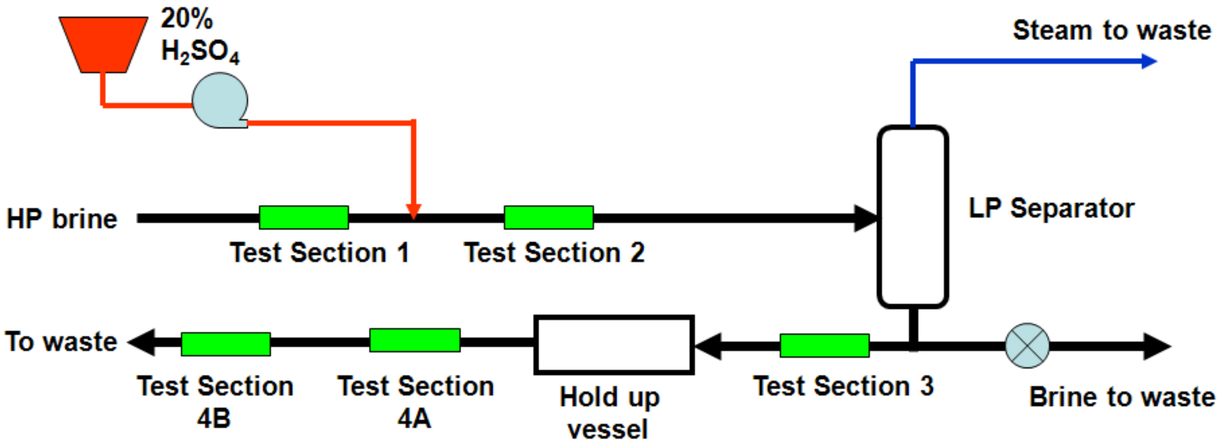

Figure 3: Simplified schematic of Flash Rig

As the reservoir temperature is lower at Ngatamariki than the Rotokawa and Kawerau fields, a dual-flash process was initially proposed and tested, as illustrated in Figure 3. Layout of the plant was such that the plant could be converted to triple-flash upon the conclusion of dual-flash trials, if required. Three main trials were conducted for the flash rig, with details of each trial given in Table 2.

	Trial 1	Trial 2	Trial 3
HP Separation Pressure (barg)	14.1	13.0	13.0
LP Separation Pressure (barg)	1.7	0.99	0.44
LP Silica Saturation Index	1.85	2.1	2.5
Target pH_{25}	5.00	5.00	5.00

Table 2: Flash rig trial conditions

With the design of the plant aiming to maximise electricity production, at an early stage of planning it was recognised that for any flash plant development acid dosing would be required. Previous flash rig experiments (Brown and Rock, 2010) conducted at Kawerau concluded that acid dosing was required upstream of the brine pressure reduction valve between the HP and LP separators to delay silica polymerisation from starting, therefore acid was added into the HP brine where the SSI for amorphous silica was <0.9.

Acid dosing was conducted for all flash trials, with a target pH_{25} of 5.0 in the LP brine. Sulphuric acid (~20% strength) was injected directly to the separated HP brine, based upon a HP brine flow ratio controller. Unlike previous test rigs which struggled to maintain stable pH, the Ngatamariki test rig was able to do this with suitable acid delivery pumps, a slight temperature trim and most importantly with stable flow rates in the HP brine flow. Stability in flow rates was achieved by making use of an automated waste-gate to control LP separator level. Utilising 20% sulphuric acid enabled easier control than had 98% sulphuric acid been used, with the titration curve shown in Figure 4.

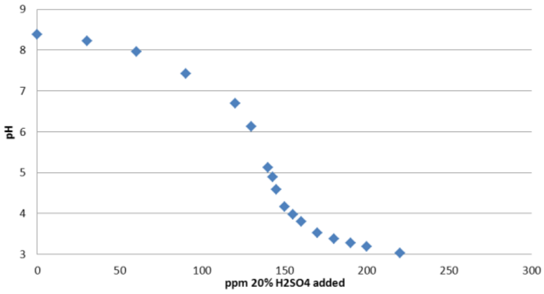

Figure 4: Measured pH titration curve for 20% sulphuric acid addition, for pH measurement in the LP brine and acid addition into the HP brine

2.2 Scaling Results

At the conclusion of each trial (~ 2-3 weeks), the test pipe sections were removed, cooled, drained, washed immediately with distilled water, and then dried. Using a non-lubricated hacksaw, samples of the test sections were cut at a point ~ 60 cm from the inlet flange to avoid any effects due to turbulence from the connecting flanges.

In addition to taking high-magnification images, the SEM was also used for elemental analysis using energy dispersive x-ray analysis (EDX). Both the top and bottom of the pipe were analysed. Prior to analysis with the SEM, the scale on the surface of the samples was described using a binocular microscope and were also photographed with an optical microscope.

An additional 5-6 cm section of each test pipe was also cut and sawn along the horizontal length of the pipe, exposing top and bottom internal surfaces. The hemi-cylindrical samples were weighed, and then the scale on the internal surface was removed by scraping and the samples were weighed again. The area of the cleaned internal surface was then measured, providing a comparative scaling rate for the different sections tested. When coupled with the time that the samples were exposed, it provides a normalised scaling rate in gms.m^{-2}.day^{-1}.

Flow in the HP section, where test sections 1&2 were located, was 10 t/hr. To compensate for the larger flow rates, these test sections utilised a 50mm nominal diameter carbon steel pipe compared to test sections 3&4 which used a 20mm nominal diameter carbon steel pipe as the LP section flow rate was 2 t/hr. The change in diameter was to ensure a consistent velocity across test sections throughout the plant.

Test section 1 in all trials featured a very low scaling rate, which is to be expected as silica is undersaturated with respect to amorphous silica. In all trials silica was present, but the suspected cause of this was the plant shutdown where the plant is cooled and some flashing occurs upon removal of the test section. In trial 2, evidence of corrosion due to acid dosing startup and shutdown was present. Minimising the time between acid dosing shutdown and plant shutdown is important to prevent scaling, however acid dosing must always be shutdown prior to the plant being shut down to prevent unnecessary corrosion damage.

Evidence of acid attack on the piping was also evident for test section 2 for trial 2. Unusual metals to be found immediately after acid dosing due to the low pH included Ag, Au, Sb and As. These were present not necessarily as a sulphide. Algae contamination of these test sections was a problem throughout all trials, as seen in Figure 5.

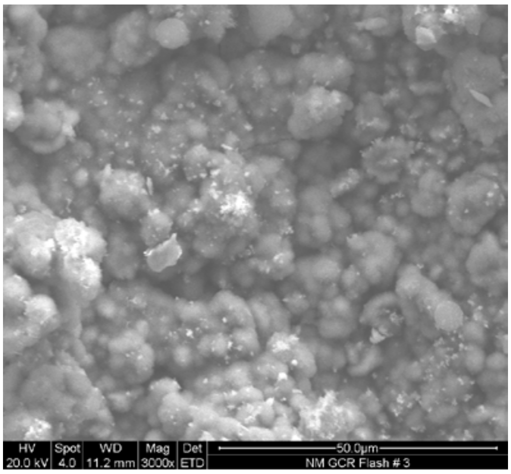

Figure 5: SEM photomicrograph of scale from acidified HP brine test pipe section with algae contamination

	Scaling Rates ($g.m^{-2}.day^{-1}$)		
Test Section	**Trial 1**	**Trial 2**	**Trial 3**
3	0.50	2.99	6.56
4	0.89	3.06	5.28

Table 3: Scaling rates for LP Brine test sections before (3) and after (4) holdup

Scaling rates for test sections 3&4 (Table 3) increase with a decreasing LP flash pressure. All deposits were colloidal with ridges present and were similar for all trials. A photograph is shown in Figure 6, showing the orange nature of the sample which is algae contamination.

Figure 6: Test section 3, trial 2, showing a cut open section of pipe, flow from left to right and top of pipe on top.

The design of the holdup vessel was a large cylinder on its side with an Archimedes screw inside, turning at a low velocity as not to stir fluid inside. Understanding the profile of the holdup was important for the results of the final test section. To understand this, tracer flow testing gear was used to inject a slug dose before the holdup vessel and samples were taken each minute and analysed to give the holdup vessel retention curve (Figure 7). This indicated that the mean holdup time for 2 t/hr flow was ~55 minutes, with a minimum time of 40 minutes and a maximum time of 80 minutes.

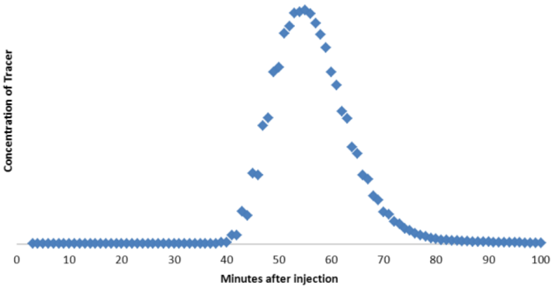

Figure 7: Holdup vessel retention curve

Elemental analysis of the scale on the final test section (Table 4), corrected for carbon removal, indicate that silica is the significant contributor to the scale formed. However, when compared to the reservoir concentrations (Table 1), arsenic and antimony tend to deposit quantitatively more, comparative to silica. Arsenic deposition, as a proportion of the overall deposit, is consistent throughout all trials whilst antimony deposition decreases with lower temperature which is indicative of deposition elsewhere in the plant upstream of the test section.

Element	Trial 1 (wt %)	Trial 2 (wt %)	Trial 3 (wt %)
O	13.26	15.08	20.39
As	5.44	6.17	7.21
Al	3.15	4.74	4.57
Si	25.77	39.47	45.9
S	3.64	5.12	7.5
Sb	36.04	12.78	2.34
Fe	12.63	14.13	8.79

Table 4: Deposit composition for the final test section (4) after holdup

2.3 Polymerisation Results

Apparatus to measure the polymerisation rate of the silica was attached to the outlet of the LP separator. This consisted of an inner chamber of ~ 1 litre capacity, surrounded by an outer chamber to maintain temperature control. Brine was fed to the inner chamber with the inner chamber then being closed. Brine was flowed around the outer chamber continuously to maintain a constant temperature. A small sample was taken from the inner chamber at 10-15 min intervals and the concentration of monomeric silica analysed.

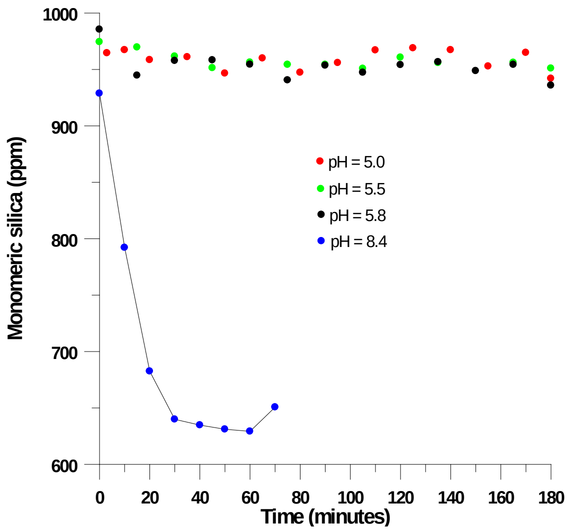

Figure 8: Silica Polymerisation curves from Ngatamariki with a second flash pressure of 1.7 barg and varying pH

Factoring in the scaling results, an LP flash pressure for Ngatamariki would be set at 1.7 bar(g). Figure 8 shows the monomeric silica concentration is maintained for up to 180 minutes with an LP pH_{25} of 5.0, 5.5 and 5.8. However, with no pH modification polymerisation begins immediately and the brine is fully polymerised after 30 minutes. The conclusion of this work was that for an LP separation pressure of 1.7 bar(g), a pH_{25} 5.0, silica will sufficiently delay silica polymerisation and there will be flexibility for pH excursions without significant polymerisation.

3. BINARY RIG

A key design point of the binary plant is where to add the steam condensate into the brine. Due to gases dissolving in the condensate, it naturally has a low pH which assists with lowering the pH when added to the brine. This low pH via condensate addition is advantageous as it enables silica control without the need for further acid dosing, reducing complexity as well as cost. Addition of condensate also has a dilution effect, assisting with reduction of brine SSI.

Condensate addition to the brine can occur at one of two locations:

- Prior to the preheater. This reduces the pH, assisting in reducing the likelihood of silica polymerisation as the pH is reduced before the silica saturation index is exceeded. However this reduction in pH increases the likelihood of antimony and arsenic sulphides (Brown, 2011) depositing within the preheater itself, reducing efficiency of the unit as deposition occurs. The amount of energy taken out of the condensate prior to mixing is not as relevant, as additional energy is taken out in the preheater;

- After the preheater. The silica concentration of the brine through the preheater is higher, as is the pH, increasing the risk of silica polymerisation occurring. The addition of condensate after the preheater also results in needing to take more energy out of the condensate in the steam condenser section.

As seen in Figure 9, the design of the test rig was such that condensate addition could occur either before or after the preheater. In addition to this, condensate addition before the preheater could be moved before or after test section 5, allowing for the option of understanding the impact of acid dosing, which would occur after test section 5. All trials conducted had condensate addition after test section 5 without acid dosing.

Steam was condensed and cooled to ~185˚C and degassed at 12.5 bar(g). The condensate (0.41 t/hr) was then mixed with the incoming HP brine (1.59 t/hr) producing a combined flow (2.0 t/hr) of ~190˚C. The combined flow then passed through a brine heat exchanger, the preheater, where the temperature was decreased to the target set-point of the trial (Table 5). The resultant reinjection temperature is also a key parameter which must be tested on the test rig. A reduction in temperature affects all key scaling constituents; silica, arsenic and antimony.

Four 20 mm nominal diameter carbon steel test sections (5-8) were flanged into the brine flow throughout the process. The heat exchangers consisted of multiple stainless steel ¾" tube and after each trial one was removed from the preheater and cut into sections for analysis along the combined fluid flow path. A new tube was installed prior to the next trial taking place. All samples were all analysed as per the flash rig trials.

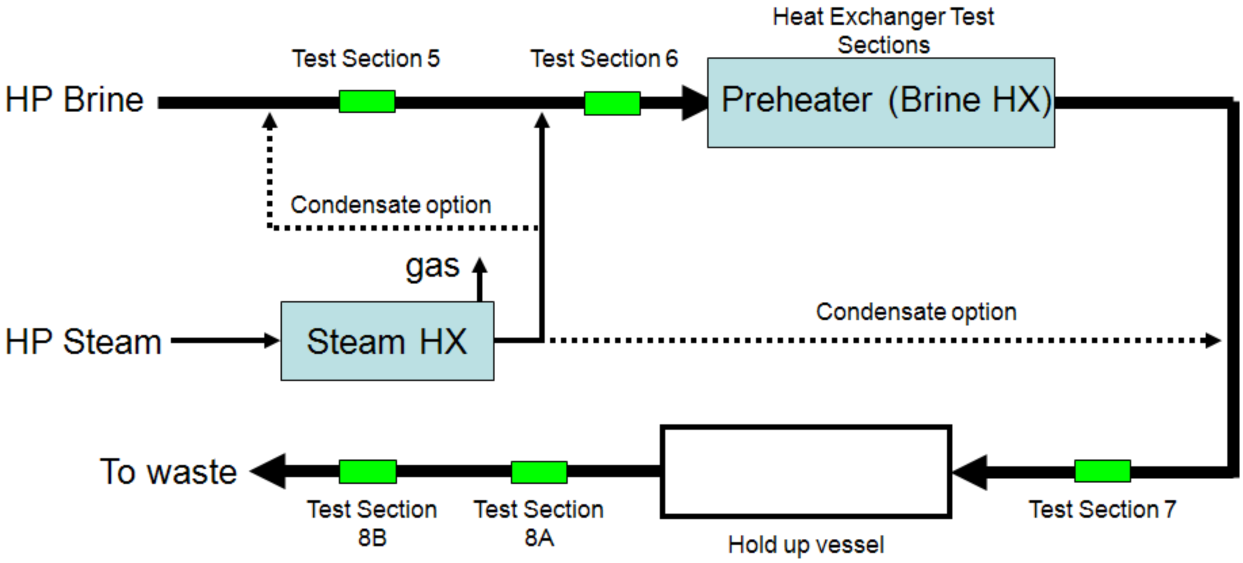

Figure 9: Simplified schematic of Binary Rig

Three trials were conducted on the binary rig. The original design basis for the plant was for a brine heat exchanger exit temperature of 85˚C, therefore the first trial was intended to be above this to allow for comparison. When trial 2 was concluded, due to large quantities of arsenic sulphide deposition, trial 3 was conducted with an exit temperature of 90˚C to understand better the boundary conditions for this arsenic sulphide deposition.

	Trial 1	**Trial 2**	**Trial 3**
Brine Silica Saturation Index (prior to condensate addition)	0.88	0.88	0.88
Condensate addition after which test section	5	5	5
Brine Silica Saturation Index (post condensate addition)	0.78	0.78	0.78
Brine Heat Exchanger exit temperature (˚C)	95	85	90
Brine Silica Saturation Index (upon exit of heat exchanger)	1.87	2.16	2.04

Table 5: Binary rig trial conditions

3.1 Results

Test section 5 in all trials featured a very low scaling rate, which is to be expected as silica is undersaturated with respect to amorphous silica. Any scale formed is suspected to be due to shutdown, as per the flash plant. The scale that did form was shown to be silica with significant amounts of aluminium co-deposited (Al/Si = 17%).

After steam condensate is mixed into the HP brine a black coloured, thin, soft, easily removed scale was present. Under the SEM (Figure 10), the deposit was seen to consist of small (~ 5x5x0.15µm) plate-like crystals. This deposit was almost entirely iron sulphide, in an approximate 1:1 atomic ratio, potentially indicating the mineral pyrhotite.

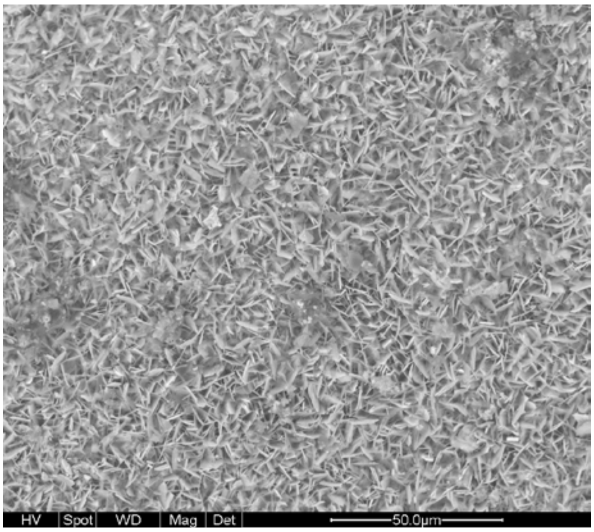

Figure 10: SEM photomicrograph of scale from immediately after steam condensate addition (6) from Trial 3

Test section 7 was located immediately after the preheater. For all trials antimony sulphide deposition was significant, and to a lesser extent arsenic sulphide. The deposit has a purple colour on the surface, which becomes more red underneath. Evidence of some colloidal ridge deposition starting was present, with colloid sizes typically in the range of 3-5µm (Figure 11). The measured pH_{25} after the brine heat exchanger was ~5.6.

Scaling rates for test section 7 and 8 for each trial are shown in Table 6. Some error in scaling rates for trial 1 are expected due to the short nature of the trial, completed early due to a plant part malfunction.

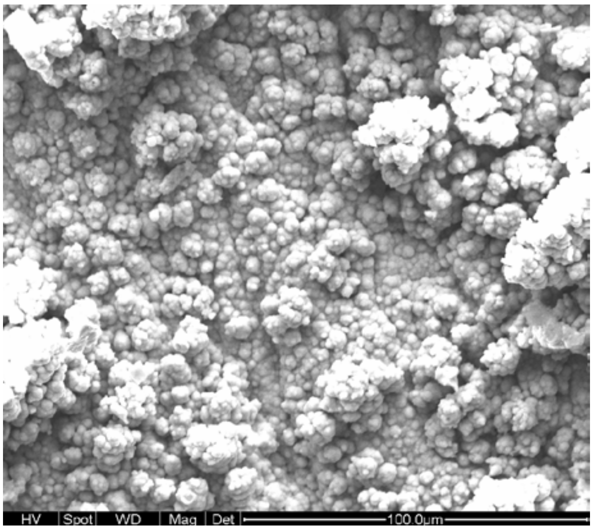

Figure 11: SEM photomicrograph of scale from after the preheater (7) from Trial 2

	Scaling Rates ($g.m^{-2}.day^{-1}$)		
Test Section	**Trial 1**	**Trial 2**	**Trial 3**
7	0.70	2.37	1.15
8	1.81	6.53	1.10

Table 6: Scaling rates for test sections 7&8

After holdup of an average of 55 minutes, the fluid flowed through test section 8. When compared to actual plant reinjection line temperatures, the test plant had an additional temperature drop of ~2-3˚C for this test section.

For trials 1 (95˚C) and 3 (90˚C), the deposit is thin and colloidal ridges are present perpendicular to the flow. The deposit is dark black/purple and is easily removed. The deposit is a mixture of antimony, arsenic and iron sulphides in a similar deposit to that found at test section 7.

For trial 2 (85˚C), a significant quantity of deposit formed in this location. The deposit is orange/brown in colour and is very soft and easily removed. Upon EDX analysis of the deposit, the rods showed that they were mainly arsenic sulphide, with much smaller amounts of antimony and iron sulphides. No silica was observed, other than some remnants from plant shutdown. At high magnification (Figure 12) the arsenic sulphide rods can be seen to be cylindrical, with diameters of 0.2-2μm and lengths in the range of 5-20μm.

The rather large amount of scaling only occurred after a hold-up period for trial 2, and therefore might be expected to deposit in the injection formation, leading to potential for a reduction in injectivity. Lowering the pH reduces the solubility of both arsenic and antimony sulphides, therefore the solution was to increase the reinjection temperature to 90˚C.

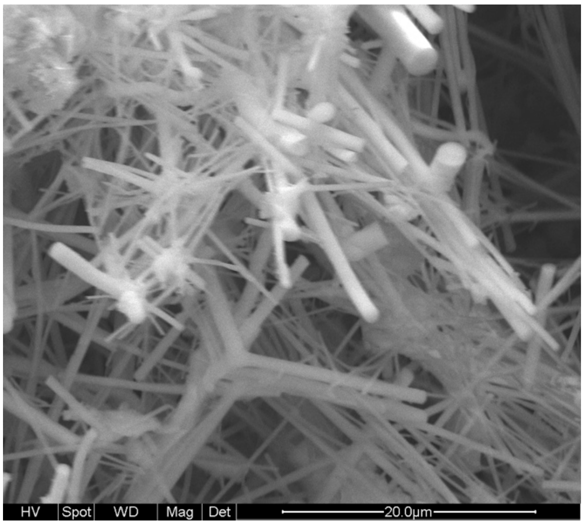

Figure 12: Arsenic Sulphide scale seen in trial 2 for an exit temperature of 85˚C

The preheater is a co-current shell and tube unit with stainless steel tubes. At the completion of the experiment, the tube bundle was extracted and one tube was cut for samples. 14 samples of stainless steel were retrieved along the temperature gradient, labelled HX1 to HX14, with HX1 being at the hot entrance. The deposit on all the heat exchanger tubes was very thin, soft, non-adherent and easily removed. As the samples cooled the purple nature of the samples darkened (Figure 13).

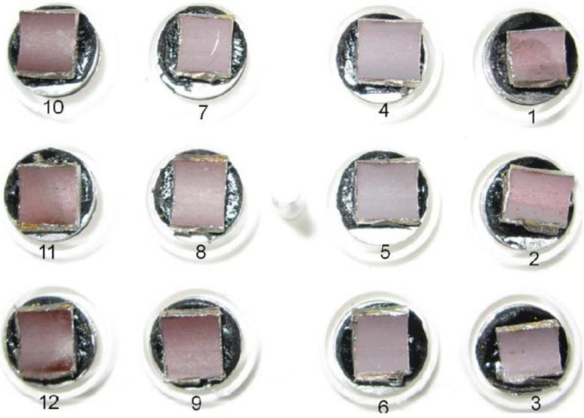

Figure 13: Brine heat exchanger tube samples for trial 3. HX1 being at the entrance (hot end) and HX12 closest to the exit (cool end) of the heat exchanger. The lighting of the photography does not record accurately the shades of colour in the samples.

When viewed under SEM, the deposit is seen to be colloidal in nature in the initial samples (Figure 14). The colloids early on in the heat exchanger are whole, but start to show holes in the surface with the decrease in temperature. This is possibly due to the heating and loss of liquid during sample preparation. The colloid size is 2-4μm, similar to the other trials. By the sample at HX8, the colloids have become more open and porous (Figure 15). As the fluid is cooled further in the heat exchanger, the colloids appear to have become sparse and bare metal is visible (Figure 16)

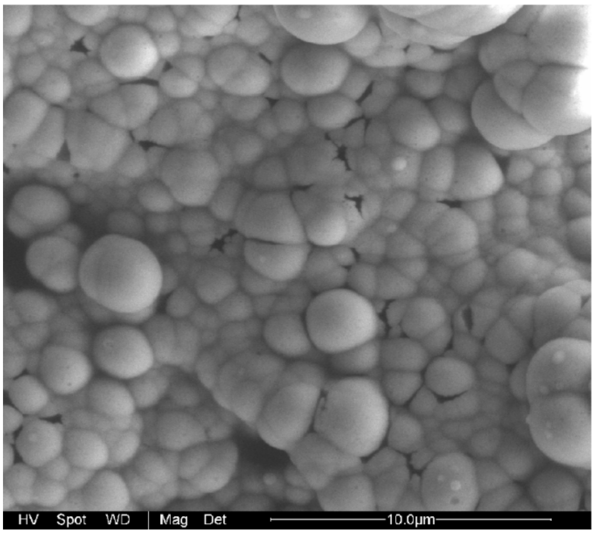

Figure 14: SEM image of the deposit on HX1, trial 3

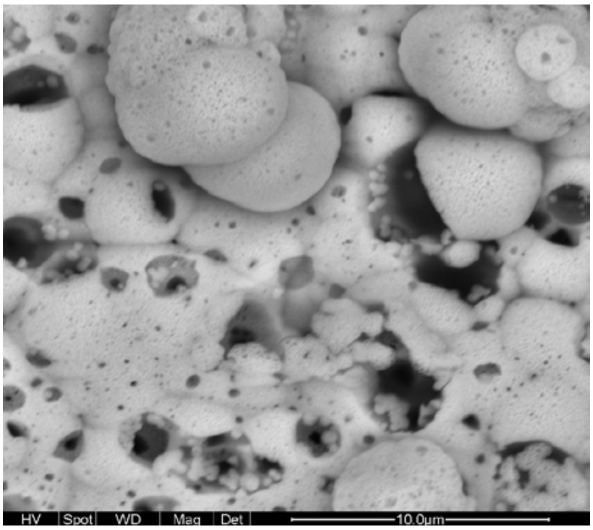

Figure 15: SEM image of the deposit on HX8, trial 3

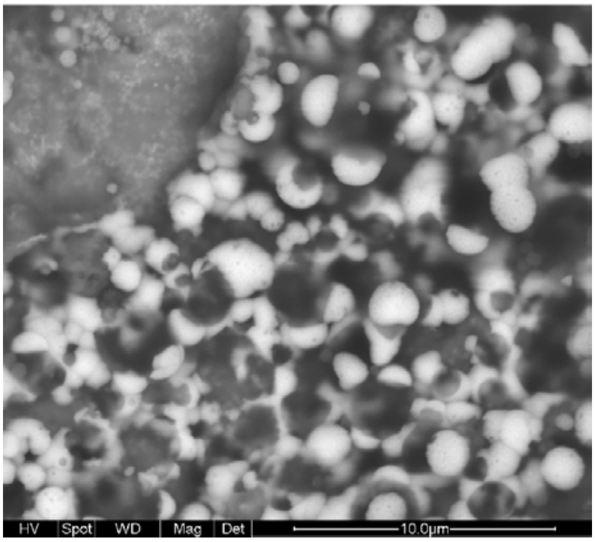

Figure 16: SEM image of the deposit on HX11, trial 3

As the mixture is cooled, antimony sulphide deposits more than arsenic sulphide. Due to the high H_2S concentration available in the condensate, antimony sulphide is expected to be formed, as compared to elemental antimony. The main product formed in the heat exchanger at Ngatamariki was amorphous antimony sulphide (red colour) rather than crystalline stibnite (black). Averaging results along the heat exchanger, a ratio of 4:1 antimony to arsenic exists in the deposits. Early on in the heat exchanger a significant iron compound present as a sulphide is present, thought to be an artefact of the low pH in the condensed steam, which then reacts with the carbon steel pipework in the condensate pipeline.

The deposition of antimony and arsenic sulphides will affect the heat transfer as the thickness of the deposit increases. Methods of removing this deposition is important, such as chemical (Dorrington and Brown, 2000) or mechanical cleaning. Assuming 95% quantitative deposition of the antimony as an amorphous sulphide results in the formation in each unit of 275 kg per 6 months. Using the 4:1 ratio of antimony to arsenic, an additional 70 kg of arsenic sulphide deposition will occur over that period.

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