# Scaling Mitigations for the Binary Plant Vaporizer: Upper Mahiao, the Philippines

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**Keywords:** *Brine plant, scaling problem, hydrofluoric acid cleaning, Upper Mahiao, Leyte.*

## ABSTRACT

The Upper Mahiao (UM) binary plant, Leyte the Philippines has two scale deposition problems in the binary fluid vaporizer: (1) the recurring clogging of vaporizer inlet with solid particles and (2) the fouling (mineral scaling) of the vaporizer tubes with silicate scale. After the last plant shutdown in November 2012, a rehabilitation program was conducted in 2015. This study includes additional mitigation and prevention of scaling: (1) calculate the configuration of the heat transfer area of the vaporizer and (2) evaluate silica removal using hydrofluoric (HF) acid solution based on the experience at the Wairakei binary plant, New Zealand.

The calculation of the vaporizer reconfiguration shows that more than 10% of the total number of tubes is plugged so this method will not be followed. Silica scale removal using hydrofluoric (HF) acid solution with the ongoing use of inhibitor is found to be the best silica removal option for the clogged UM brine plant vaporizer with hardened silica deposits. The main advantages of this method are the lower cost and shorter cleaning time compared with water blasting and mechanical cleaning. The study also demonstrates that all environmental concerns for using the acid will be avoided since the chemical will be disposed directly into the reinjection well.

## 1. INTRODUCTION

The upper Mahiao brine plant is an ORMAT Energy Converter (OEC) commissioned in 1996. It utilizes high temperature (~190°C) separated geothermal brine. The brine vaporizes pentane in a single-pass shell and tube heat exchanger also known as the vaporizer (Figure 1). Its installed capacity is 4.6 MWe with brine flow requirement of 350 kg/s. The brine velocity requirement at the vaporizer tubes is 1.5 m/s and the brine residence time is 11 sec in the vaporizer.

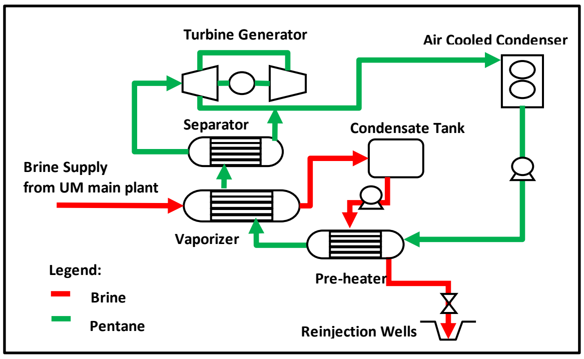


**Figure 1: Simplified diagram of UM binary plant.**

The brine silica concentration is 687ppm at an average line temperature of 188°C in the measurements from 2007 to 2014 using saturation temperature at sampling point pressure. This silica concentration at this temperature indicates under-saturation with amorphous silica based on the temperature dependence of the solubility of quartz and amorphous forms of silica (Zarrouk S. W., 2014). However, at this amorphous silica saturation concentration, it is still likely to precipitate having been affected by the decrease in temperature during the heat transfer process. Monitoring data suggested the presence of deposits on the vaporizer tube walls and blockage of the vaporizer tube inlet by debris which was confirmed after documentation (Jamero, 2014). In a 2012 analysis, scale samples were composed of 80% amorphous silica, 10% impurities and 10% corrosion products. The deposition in the tubes is composed of loose, very fine fragments with 49% amorphous silica, 40% corrosion products, 10% rock fragments and 1% cement fragments as analysed by Rosell in 2012 (Jamero, 2014).

After years of operation since its commissioning, there was a significant decrease in the brine supply of about 100 to 170 kg/s, which resulted in an intermittent shutdown of the brine plant. In 2006, it was rehabilitated and tested briefly with a higher temperature drop of 40°C. For five years thereafter, it was on shut down and then was rehabilitated again but with intermittent operation from May 2011 to November 2012. Table 1 shows the summary of the vaporizer observations during shutdown (Jamero, 2014).

**Table 1. Summary of observations during the shutdown.**

| | Date | Reason for Shutdown | Vaporizer Observations |
|---|---|---|---|
| 1 | 22/06/11 | Declining generation | Significant amount of debris in vaporizer inlet |
| 2 | 04/01/12 | Pentane leak | Minimal debris in vaporizer inlet |
| 3 | 29/01/12 | Low net load (<0.5 MWe) | More debris relative to shut down 2 |
| 4 | 21/02/12 | Switching activity; high vaporizer pressure | Minimal debris in vaporizer inlet |
| 5 | 02/03/12 | Pentane leak & low net load | Minimal debris; flaky solids inside vaporizer tubes |
| 6 | 16/05/12 | Sudden drop in output load | Minimal debris in vaporizer inlet; in situ deposits in tubes |
| 7 | 27/09/12 | Decrease in output load | Flaky solids in vaporizer inlet and tubes |
| 8 | 17/11/12 | Declining generation; leaking tubes | Decreased tube diameter due to depositions |

Initially, major debris accumulation was observed but flushing and continuous utilization reduced the debris. These foreign materials inside the vaporizer prevented the flow of brine and decreased the vaporizer heat exchanging efficiency. This eventually decreased the generated power output leading to the economic shutdown of the brine plant. Since the last shutdown in 2012, there were no significant activities to revive the power plant until in 2015 when the rehabilitation programme was launched in the attempt to operate the plant at a lower brine supply of 130 kg/s which is estimated to generate 2.0MWe energy and to address the recurring deposition problem for sustainable operations.

The rehabilitation programme includes the removal of the hardened silica deposition at the vaporizer tubes using various methods such as water blasting and mechanical cleaning, but these methods were unsuccessful and were stopped due to the slow rate of progress. Another part of the programme is to conduct induction time testing to determine the dosage of chemical inhibitor to prevent silica deposition inside the vaporizer but the series of tests were unsuccessful because the required brine velocity that replicates the target operational velocity was not attained during testing. Also, part of the program is the installation of baffles in the 42" solid trap to modify existing solid traps to efficiently capture the corrosion products and prevent carryover to the vaporizer, and the installation of two additional basket strainers near the vaporizer inlet to address the issue of corrosion products depositing at the inlet of the vaporizer; however, the installation is yet to be done pending arrival of the equipment.

The purpose of this study is to propose additional mitigation and prevention of silica deposition for the sustainability of the brine plant operations. The following areas will be investigated to make use of the available data:

(a) Determine the possible number of tubes that can be plugged to reconfigure the heat transfer area of the vaporizer to increase brine flow rates.

(b) Evaluate the applicability of hydro flouric acid for silica deposits removal in Upper Mahiao brine binary plant based on the experience in Wairakei binary plant, New Zealand.

## 2. SCALING PROBLEMS AT THE VAPORIZER

Silica scaling is common in geothermal heat exchangers because silica has a prograde solubility that reduces with temperature (Zarrouk S. W., 2014). The brine utilized in the brine plant is transported from the main plant and the temperature is reduced along the line and during the heat transfer process, so it is expected that there would be likely silica deposition in the vaporizer tubes. The mixture of separated brine and steam condensates will reduce the silica scaling potential (Zarrouk S. W., 2014); however, the extent of the deposition still greatly depends on the brine chemistry and flow rate. The decrease in flow rate increases the pressure drop and the residence time of the brine at the vaporizer which will result in increased silica deposition in the vaporizer tubes.

Silica deposit is formed as a result of its polymerization, co-precipitation with other minerals, precipitation with other multivalent ions, and biological activity in the brine (Gill, 2008). Silica in its solid phase (silicon dioxide) is identified in its crystalline form (quartz) or non-crystalline form (amorphous silica). There are two forms of silica deposit, the silica that dissolves in water forming amorphous silica deposition induced by silica polymerization and the silicate that are formed when ionized silica reacts with metals such as Ca, Mg, Al, Fe, Zn, etc (Gill, 2008). Silica deposition occurs either by molecular deposition or homogeneous nucleation (Zarrouk S. W., 2014). In molecular deposition, silicate species in solution bond directly on the surface such as vaporizer tube wall, while in homogeneous nucleation, dissolved silica undergoes reaction process forming polymer chains which flocculate to form low-density silica scale (Zarrouk S. W., 2014).

Major drivers for silica scale formation are the decreasing temperature, near-neutral pH, and increasing dissolved silica concentrations (Finster, 2015). General mitigation options are the modification of system operating conditions to minimize oversaturation by maintaining brine flash pressure and temperature, modification of geothermal fluid pH by acid dosing to control amorphous silica and silicate scale deposition, and modification of geothermal fluid using non-pH adjusting additives (Finster, 2015).

In Upper Mahiao main binary plant, massive scaling was due to mixing of the acidic supersaturated fluid with the less acidic fluid which resulted in a supersaturated fluid with amorphous silica, the increase in pH resulting in faster oligomerization that caused rapid scale formation (Bermejo, 2015). Based on their investigation of the massive scaling phenomena in UM, the change in pH could have triggered the massive deposition in the two-phase header, when the acidic-amorphous silica-supersaturated fluid from W2D mixed with the neutral fluid from W1D. While for the case of South Sambaloran, deposition in separator brine line was due to the flashing of the brine which caused amorphous silica to become supersaturated and deposit as scales.

### 2.1 Clogging of the vaporizer inlet

The clogging of the vaporizer inlet is due to the transported corrosion products accumulated in the brine line (Figure 2). These clay-like materials blocked the bottom tubes (Jamero, 2014). This reduced the flow of the brine inside the vaporizer tubes resulting in the decrease in the brine flow rate thereby decreasing the power plant output which caused intermittent power plant operation and eventually the plant was shut down. The amount of this flake-like debris in the vaporizer inlet can be reduced through flushing when the brine plant is continuously operated.

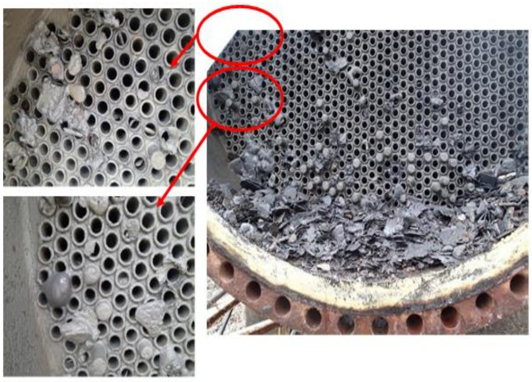

**Figure 2. Documented flakes and clay-like debris in the vaporizer inlet. The red circles show enlarged pictures of two areas with significant scale deposition.**

### 2.2 Fouling of vaporizer tubes

Fouling is the accumulation of unwanted deposits on the surfaces of the heat exchanger that causes resistance to the transfer of heat, therefore reducing the efficiency of the heat exchanger (Bott, 1995). The fouling factors of the vaporizer tubes with silica scales are mainly the Upper Mahiao brine quality and the rate of deposition being greatly affected by the decrease in brine supply over a long period of operation. The documentation during the last shutdown as shown in Figure 3 showed that the walls were heavily covered with deposits and the outlet side had decreased tube diameter due to deposition (Jamero, 2014).

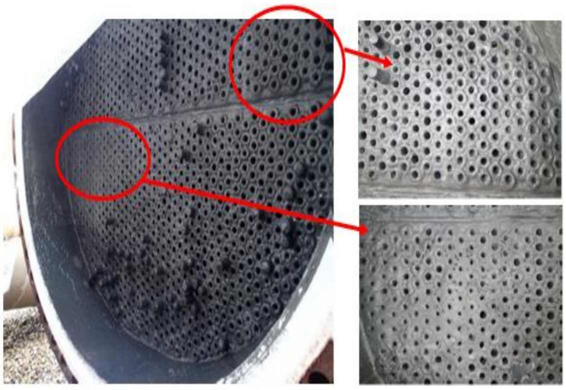

**Figure 3. Deposition in the tubes as seen in the vaporizer outlet. The red circles show enlarged pictures of two areas with significant scale deposition.**

The effects of brine quality can be evaluated by determining the thermal stability of amorphous silica with respect to pH and temperature. Figure 4 shows the stability map for amorphous silica based on a 270°C reservoir and 100 psi 1st flash pressure by Paul Hirtz (Kaplan, 2004). Amorphous silica is thermodynamically stable above 165˚C and at lower temperature and high pH values greater than 8, while it is kinetically stable at temperatures below 50˚C and pH values less than 4. Thermodynamic stability prevents any possibility of scale deposition, while kinetic stability results in an extended period before deposition occurs (Kaplan, 2004).

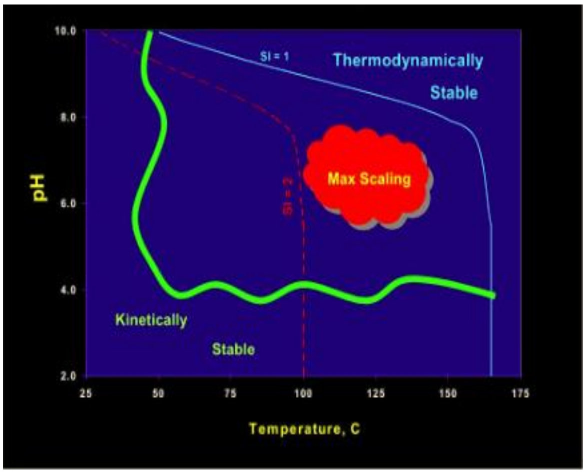


**Figure 4. Silica stability map for amorphous silica at 270°C** (Kaplan, 2004)

From the data in Table 2, the brine pH of Upper Mahiao is greater than 5.6. The silica stability map in Figure 4 suggests that for the silica in the brine to be kinetically stable at all temperatures, the pH should be less than 4, thus the brine in Upper Mahiao is considered not kinetically stable (Telen, 2015).

**Table 2. Brine pH in Upper Mahiao (2011 to 2012)***

| | minimum | maximum | average |
|---|---|---|---|
| pH | 5.55 | 6.15 | 5.71 |

*recorded temperature range of 170°Cto 190°C

A study on mitigation of silica deposition was conducted by pH modification and Geo SX injection to minimize silica deposition in Malitbog reinjection wells (Alcober, 2005). In this study, pH was adjusted from 6.8 to a range of 5.3 to 5.6 using sulphuric acid ($H_2SO_4$), and resulting in no silica being deposited anywhere in the line. However, in this test, the corrosion rate was relatively high. This corrosion was triggered because of the instances of overdosing as well as the intermittent dosing of acid. With the Geo SX which was used as the inhibitor, the results showed that deposition still occurred in the inspection pipe and formation materials but at a very low thickness and deposition rate (2.4 to 11.9 mm/year). The pH modification appeared to be the most cost-effective mitigating solution to silica deposition in Malitbog.

As part of the rehabilitation program, a crab cooker (Figure 5) which will act as the polymerization vessel will be fabricated to be used for the induction time testing as well as the right dosing of chemical inhibitor to improve the kinetic stability as well as the brine quality of Upper Mahiao (Telen, 2015).


**Figure 5. Crab cooker configuration**

The thermodynamic stability of the silica in the brine can be evaluated through its Silica Saturation Index (SSI). Data regarding the brine SSI in Upper Mahiao is presented in Table 3.

**Table 3. SSI values corresponding to temperature of the brine from 2007 - 2014**

| | At minimum temperature | At maximum temperature |
|---|---|---|
| Line Temperature, °C | 178 | 196 |
| SSI | 0.94 | 0.69 |

The Silica Stability Map in Figure 4 suggests that at an SSI value of 1, the silica in the brine is thermodynamically stable. For the stability to be sustainable in the system, the brine plant can be operated at a brine outlet temperature greater than 170°C, keeping the SSI less than 1. Brine SSI levels become supersaturated at the vaporizer outlet due to temperature decline. The minimum outlet temperature of brine in the vaporizer should be about 150°C for a maximum allowable SSI of about 1.2 which can be observed in Figure 6, an SSI vs. temperature graph applicable to Upper Mahiao (Telen, 2015).

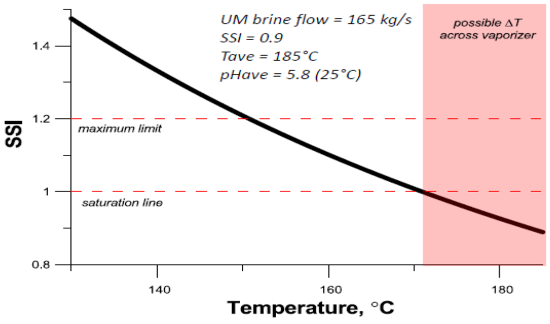


**Figure 6. SSI vs. Temperature** (Telen, 2015)

Silica deposition within the tubes is a result of the combined effects of the silica saturated brine (SSI=1.0 to 1.1) caused by the temperature drop, and increased residence time (average of 35 seconds) due to low brine flow (Jamero, 2014).

The data during the brine plant operation from November 2011 to June 2012 in Figure 7 (Jamero, 2014) show brine SSI levels at the inlet of the vaporizer indicating silica is under saturated. However, the outlet SSI values are supersaturated. The silica super saturation at the vaporizer outlet is due to the decline of temperature.

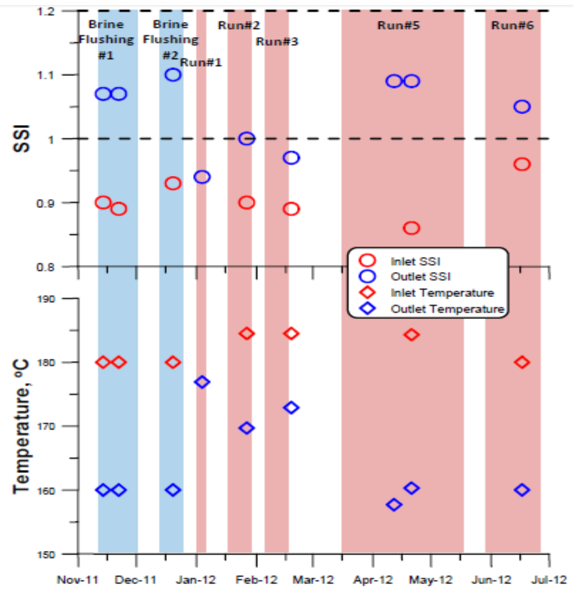


**Figure 7. SSI and temperature data** (Jamero, 2014)

The intermittent brine plant utilization data in Figure 8 (Jamero, 2014) shows the summary of the seven previous runs. The highest brine supply was ~170 kg/s in run 2 and after that it started to decline. Maximum gross generation of 2 MWe was attained in run 5 at ~120 kg/s brine flow rate. After the brine flushing and vaporizer cleaning prior to the start of run 6 and run 7, there is still no significant increase of generation due to the declining supply of brine which caused the increase in brine residence time at the vaporizer and resulted in silica deposition. Fouling of the vaporizer tubes resulted in the reduction of the brine to flow through the vaporizer, this leading to the decrease in the temperature drop and increase in the pressure drop. Decrease in the temperature drop indicates that the heat transfer of the vaporizer is inefficient.

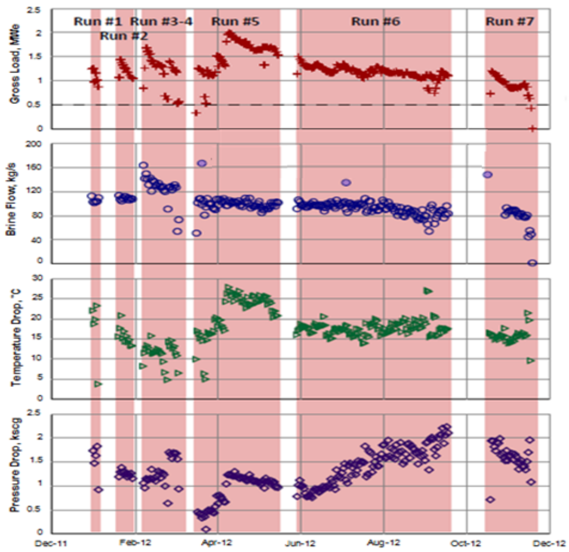


**Figure 8. Gross load, brine flow, temperature drop and pressure drop data** (Jamero, 2014)

## 3. BRINE PLANT REHABILITATION ACTIVITIES

The rehabilitation program that was started in 2015 is composed of three sets of activities: the first category includes the activities that will address the problem in the brine quality and avoids clogging of the vaporizer inlet such as the solid trap modification and installation of basket strainers. The second category is composed of activities to determine the scaling potential to mitigate the massive silica scaling problem and prevent fouling of the vaporizer tubes which includes the induction time testing and the acid dosing facility, while the third category includes the inspection, cleaning and servicing of the power plant facilities prior to power plant re-commissioning. These activities were done simultaneously; however, the brine treatment will depend on the result of the induction time testing. Some of the major activities conducted will be discussed in this paper which are the solid trap modification, basket strainer installation, induction time testing, and the vaporizer cleaning.

### 3.1 Solid trap modification

To prevent massive debris carry over, the plant has installed two solid traps upsteam of the vaporizer to capture these corrosion products. One is a 42" solid trap and the other is a 36" twin strainer-type solid trap (Figure 9). The degree of corrosion products carry over in the vaporizer inlet indicates that the existing solid traps were not very effective so there is a need for modification. The rehabilitation program includes installation of baffles in the 42" solid trap to increase its effectiveness in capturing solids carry over.

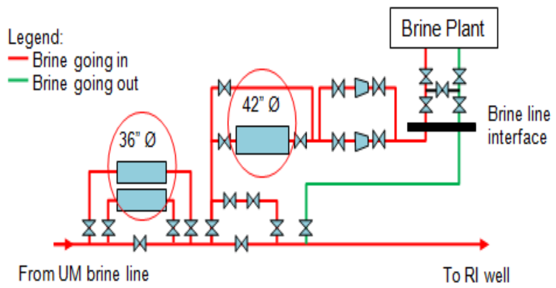


**Figure 9. Solid traps installed in the brine line**

### 3.2 Additional basket strainer installation

Basket strainers are composed of a screen or element formed like a basket with a lifting handle so the debris, solids or corrosion products captured and retained in the screen can be easily removed for disposal. To ensure that there will be no more solids carry over to the vaporizer inlet, two basket strainers are to be installed upstream of the vaporizer with the element as shown in Figure 10 (Telen, 2015). There will only be one strainer used at a time; the second strainer will be a backup when the other strainer undergoes maintenance so there will be no opportunity loss in the operation.

**Figure 10. Basket strainer element**

### 3.3 Induction time testing

The induction time test is necessary to determine the dosage of the silica scaling inhibitor. To test the effect of the dosing chemical on the silica deposition, a side stream test will be conducted to simulate the vaporizer using the crab cooker. Brine retention time in the side stream set-up should be maintained at 11seconds based on the design (Telen, 2015). Table 4 shows the list of parameters maintained, monitored and recorded during the test.

**Table 4. Parameters to be measured and monitored in the induction testing from brine inlet and outlet.**

| Constants | Chemical Parameters | Physical Parameters |
|---|---|---|
| a. Brine temperature drop = 20°C | a. pH | a. Brine flow |
| b. Brine retention time = 11sec | b. $SiO_2$ | b. Temperature |

The purpose of this test is to replicate the cooling flux of an exchanger in the coils of the crab cooker. The brine line is connected to the inlet valves. Cooling water is supplied to the drum at a separate inlet valve. The cooling water in the drum must be circulated and controlled by a temperature controller that varies the amount of cold water entering the drum to keep the temperature constant. This is done by a simple motorized valve that is controlled by a simple set temperature sensor which has a probe in the drum. The drum is filled with cooling water by manually switching on the motorized valve then the temperature sensor is submerged inside the drum and set temperature control to required temperature set point. The brine inlet valve will then be opened. The flow through the coils (baseline and treated) must be controlled by the needle valves at the outlet of the coils to avoid flashing and also used to adjust the residence time of the brine. The flow through the coils and the temperature of the water can be adjusted to simulate the conditions in the plant. The inhibitor will be injected through a line connected to a chemical pump injection valve at the tee connection located in the inlet line of the system (Figure 11). The coils are cut up later to compare the treated line with the baseline. The amount and rate of the deposits can be collected and analysed.

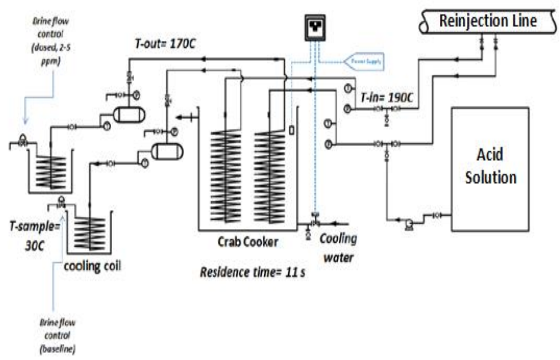


**Figure 11. Crab cooker schematic diagram** (Telen, 2015)

The crab cooker functionality test was conducted in August 2015; however, the desired flow rate was not achieved with the current set-up. Required flow rate is 3.1 L/min but only 44% of it was achieved. Another plan for the functionality test is to connect it into a brine line that meets the required stable flow rate and temperature drop. When the crab cooker is ensured to be working properly, it will then be installed along the Upper Mahiao brine line for the induction time testing.

### 3.4 Vaporizer cleaning

The Upper Mahiao vaporizer is a single pass, shell and tube type heat exchanger composed of 1,485 tubes. From the data shown in Table 5, the current flow conditions of Upper Mahiao do not meet the design requirements. Due to the decline of brine supply by more than 50%, the velocity of brine slowed down, thus increasing its residence time inside the vaporizer giving more time for the silica in the brine to polymerize (Telen, 2015). Fouling of the vaporizer tubes led to the decline in the inlet brine flow and temperature drop thus there was inefficient heat transfer. These tubes were heavily scaled with minerals of mainly silica deposits so vaporizer cleaning must be done to ensure brine flow along the tubes and increase the heat transfer efficiency.

**Table 5. Brine flow supply from Upper Mahiao main binary plant going to the brine plant.**

| | Flow (kg/s) | Velocity (m/s) | Residence Time (s) |
|---|---|---|---|
| Design brine flow | 350 | 1.5 | 11 |
| Min. brine flow | 111 | 0.50 | 23.9 |
| Max. brine flow | 151.2 | 0.64 | 17.5 |

As part of the rehabilitation program, silica removal was done using a combination of water blasting and mechanical cleaning in June 2015 and due to hardened scales, the slow rate of cleaning (1 to 2 tubes per day). The cleaning results were 461 tubes passable with water, 13 tubes totally cleaned, 74 tubes that were previously plugged, and 937 tubes were not cleaned or assessed if either clogged or passable with water since the activity was eventually stopped in August 2015 (Figure 12). Another method which is the combination of mechanical and chemical cleaning was evaluated. This includes mechanical drilling of the tubes to ensure chemicals will pass through the tubes: 1st pass of chemical cleaning to loosen silica component which includes chemical recirculation in the tubes, hydro test to check for tube leakage, 2nd pass of chemical cleaning to remove silica component, and neutralization and passivation to protect the tubes from corrosion. However, due to the large volume of chemical waste that can be produced and accumulated during the process of cleaning, the method has been put aside (Telen, 2015). The rehabilitation team is now looking into other economically and environmentally safe options to be used for the vaporizer cleaning.

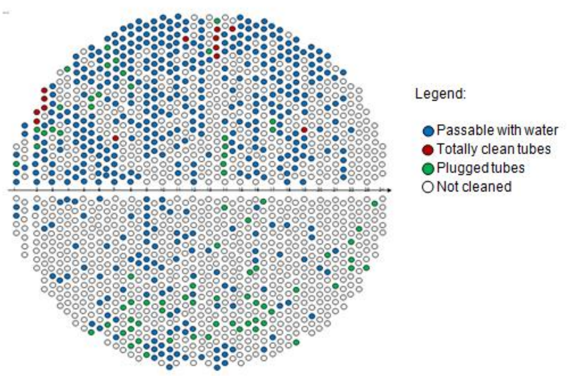


**Figure 12. Vaporizer tube status after the water blasting and mechanical cleaning in 2015**

The degree of the deposition may vary along the tubes which also affects the brine flow rate. The cleaning results showed that some tubes have increasing thickness of deposition from the brine inlet to the brine outlet. Some tubes were mechanically drilled half way in the tubes but not through to the end because of the hardened deposits. The difference of scale deposits in each tube is also affected by the accumulated corrosion products in the inlet of the vaporizer that slow down the brine velocity into the vaporizer.

## 4. ADDITIONAL MITIGATION AND PREVENTION OF SILICA DEPOSITION

To further mitigate the formation of the silica in the vaporizer tubes, consideration of the evaluation of the vaporizer reconfiguration to find out the possibility of plugging some vaporizer tubes and to find a solution in removing the hardened silica deposits in the vaporizer tubes, various methods of silica removal were investigated.

### 4.1 Vaporizer reconfiguration

To be able to decrease the residence time of brine inside the tubes, its velocity had to be increased. This can be done by reconfiguring the heat transfer area by plugging some of the vaporizer tubes to not more than 10% of its total number (Telen, 2015).

The formula below (Kern, 1965) was used to compute the number of tubes to be used to attain the desired velocity using the brine density:

$$N = (4.\dot{m})/(\rho.v.\pi.D^2) \quad (1)$$

where N is the number of tubes to be used, ṁ is the available brine flow rate of ~130 kg/s based on the maximum attained brine flow rate from the previous operation in 2012, ρ is the density of the brine of 1021 kg/m3, v is the velocity (m/s), and D is the outside diameter of the tubes of 0.0122m BWG 10. For the first calculation to attain the design brine flow velocity of 1.5m/s with a lower brine flow rate of 130 kg/s, the number of tubes to be used will only be 727 tubes which mean that there will be 758 tubes to be plugged.

The second calculation was done considering an increase in the brine flow rate to 170 kg/s assuming that Upper Mahiao main power plant will be operated at full load condition and supply additional brine to the brine plant. To attain the design brine flow velocity of 1.5m/s, the number of tubes to be used will only be 950 tubes which mean that there will be 535 tubes to be plugged.

Both of the computations using equation (1) to attain the velocity of 1.5 m/s and allow a brine residence time of only 11 seconds at the vaporizer suggest a high number of tubes to be plugged with 51% in the first computation and 36% in the second computation. The number of tubes to be plugged exceeds the 10% allowable reconfiguration and will not be applicable.

### 4.2 Chemical cleaning using hydrofluoric acid (HF) at Wairakei Binary Plant

In Wairakei binary plant, there is a temperature decrease of 44˚C from the brine inlet to the brine outlet of the heat exchanger resulting in a high level of silica super saturation which caused the silica scaling inside the heat exchanger tubes (Zarrouk et al., 2014). The silica deposition was previously cleaned by water blasting but now, chemical cleaning was done using inhibited hydrofluoric acid every six months because of its economic advantages and safety reasons (Morris, 2016).

The silica removal process uses concentrated HF (5-15%) with inhibitor which amounts to a total cost of about $100k. Assuming that the vaporizer tubes are partially clogged up, the chemical cleaning duration using HF can be completed two days earlier than cleaning by water blasting so there will be opportunity of generation for two extra days and additional revenue. This method can be done by injecting the HF to the brine at the inlet of the vaporizer. After recirculation and flushing the heat exchanger, the fluid is disposed through a dedicated HDPE line to the reinjection well so it is environmentally safe to operate. The results of HF cleaning in Wairakei binary plant also showed improvements in the injectivity of the reinjection well (Morris, 2016).

Figure 13 shows the effect of an acid cleaning on the brine inlet and outlet temperature and pressure (Morris, 2016). The brine flow as shown in the blue plot increased after the cleaning and the nominal outlet temperature of the combined fluid in the green plot is increased due to the cleanout. The pressure drop is decreasing and the temperature drop is increasing after the cleaning which indicates that the heat transfer efficiency is increasing. The generation data for the same period from October 2015 to February 2016 shows significant increase in generation for G15 generating unit after the cleaning. Wairakei binary plant also utilized periodic acid dosing along the brine which significantly slowed down the silica deposition in the vaporizer. This resulted in a reduced frequency in the vaporizer cleaning using HF, only one cleaning being needed for G15 and G16 in 2015.

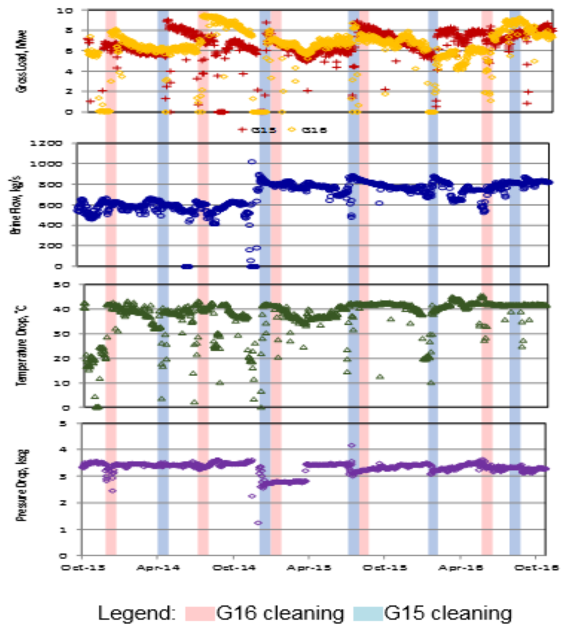


**Figure 13. Wairakei G16 and G15 Gross load, brine flow, temperature drop and pressure drop** (Morris, 2016)

Chemical cleaning using HF in Wairakei binary plant has the following advantages: (1) cost is lower by 33% than that of water blasting; (2) cleaning period is two days shorter than water blasting or mechanical cleaning; and (3) environmentally safe due to online cleaning and direct disposal of acid into reinjection wells (Morris, 2016).

### 4.3 Cost of vaporizer cleaning methods

Table 6 shows the comparison of four different silica removal methods including the previous method conducted and the three proposed options considering the total cost and duration of cleaning. The first option with a combination of water blasting for the passable tubes with soft scales and mechanical drilling for the totally clogged tubes which was tried in Upper Mahiao brine plant vaporizer but the cleaning was aborted due to the slow rate of cleaning progress of 1-2 days per tube depending on the pressure rating of the pump. The second option with the combination of mechanical and chemical cleaning using HCl has the highest total cost considering the chemical waste disposal and environmental concerns for the large volume of chemical waste that can be produced and accumulated during the process of cleaning. The cost of the third option with the combination of water blasting and chemical cleaning is comparable to the fourth option using HF but the third option still includes handling and disposal of the chemical waste while option four is carried out while the plant is online and the acid will be directly disposed to the reinjection well. The chemical cleaning using HF will be enough and there is no need for mechanical drilling of the clogged pipes as HF is effective in dissolving silica deposits.

**Table 6. Comparison of vaporizer cleaning methods**

| Method | Status | Cost ($NZ) | Tested vs Proposed |
|---|---|---|---|
| Waterblasting and Mechanical Cleaning | Tested | *44k | - |
| Mechanical and Chemical Cleaning (HCl) | Proposed | *193k | 438% |
| Waterblasting and Chemical Cleaning** | Proposed | *101k | 229% |
| Chemical Cleaning using HF acid and inhibitor*** | Proposed | 100k | 227% |

*Using Php to $NZ conversion rate of 0.03
**May contain 5-15% ammonium hydrogen fluoride ($NH_4HF_2$), 5-15% succinic acid and 70-90% water
***May contain 5-15% HF and corrosion inhibitor

## 5. CONCLUSION

The crab cooker must be ensured to be working properly before it will be installed along the Upper Mahiao brine line for the induction time testing. The results of the induction testing and the rate of deposition in the treated coil with chemical inhibitor will determine the dosing rate during continuous operation.

Two calculations were made to evaluate the vaporizer reconfiguration by increasing the velocity to be able to decrease the residence time of brine inside the tubes. One is using the available brine flow supply of 130 kg/s and the other is using 170 kg/s brine flow assuming that there will be increased brine from the Upper Mahiao main binary plant at full load operation. To attain the velocity of 1.5 m/s and allow brine residence time of only 11 seconds at the vaporizer, both calculations suggest a high number of tubes to be plugged with 51% in the first computation and 36% in the second computation. The number of tubes to be plugged exceeds the 10% allowable reconfiguration and will not be recommended.

The successful application of the chemical cleaning using hydrofluoric acid injection and recirculation in the vaporizer at the Wairakei binary plant was found to be the best silica removal option for the Upper Mahiao brine plant vaporizer that is clogged with hardened silica deposits. The main advantages of this method are the relatively lower cost and shorter cleaning duration as compared to water blasting and mechanical cleaning and environmental issues are avoided as there will be no chemical waste since the chemical cleaning will be done online and the chemical residue will be disposed of directly into the reinjection well. The disadvantage of using water blasting is the rate of cleaning is dependent on the pump pressure rating and in mechanical cleaning there is a high risk of damaging the tubes during mechanical drilling.

It is also important to have a dosing plan for the chemical inhibitor since continuous chemical dosing will have a significant increase to the operating cost. When the plant will be successfully re-commissioned and acid dosing is implemented, economic evaluation on the combination of acid dosing and chemical cleaning is recommended.

**ACKNOWLEDGEMENTS**

The author would like to express great appreciation to Chris Morris and Christine Siega from Contact Energy Ltd. for the Wairakei binary plant data. Czarina Telen for the Upper Mahiao brine plant rehabilitation data.

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