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SCALING AND TURBINE PERFORMANCE ASSESSMENT OF MAIBARARA 1 GEOTHERMAL POWER PLANT

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ABSTRACT

Turbine scaling deposition is one of the problems encountered in the first year of operations at Maibarara 1 geothermal power plant (M1GPP). To address the issue, the installation of a turbine blade washing system was recommended, but after two years of operation using the blade washing system, the turbine was inspected and scaling was still found. Data used for the analysis presented here are the results of sample deposits collected during the inspection and from the steam chemistry condensate as well as data of steam flow, turbine chamber pressure and other operational data. The turbine performance is calculated based on a Scilab modelling simulation using Stodola's cone (or ellipse) law equation. Based on the chemical analysis and the simulation the present scaling source is the washing fluid used for blade washing. Based on the assessment of the results, possible mitigation methods are presented to address the scaling formation in the turbine with regard to the performance of the turbine.

1. INTRODUCTION

The Maibarara geothermal field lies on the western flank of the inactive stratovolcano Mt. Makiling on the Island of Luzon, and was explored and initially developed by Philippine Geothermal Inc. in the 1970s (Buban et al., 1994). The Maibarara geothermal power plant is composed of two units with a total capacity of 32 MWe. The 20 MWe Maibarara 1 geothermal power plant (M1GPP) started commercial operation in February 2014, and the 12 MWe M2GPP was commissioned in April 2018. M1GPP was the first renewable energy project declared commercial under the country's 2008 Renewable Energy Law. The total estimated gross generation of both units combined is about 1.08 GWh. Despite this success and being a relatively new power plant, M1GPP encounters challenges that are affecting its operations.

Figure 1 shows the location of the Maibarara geothermal field located in the province of Batangas, approximately 70 km south of the Philippine capital city, Manila. Maibarara Geothermal Inc. operates and manages the geothermal reservoir and steamfield, generates electricity and transmits it to the grid with a service contract for a concession area of 1600 hectares (Olivar et al., 2011). The Maibarara geothermal field is a compact facility whose core project components were sited on an area of only 7.5

hectares resulting in lower installation cost, minimized environmental footprint, and more manageable operation and maintenance as shown in Figure 2.

FIGURE 1: Maibarara geothermal field location

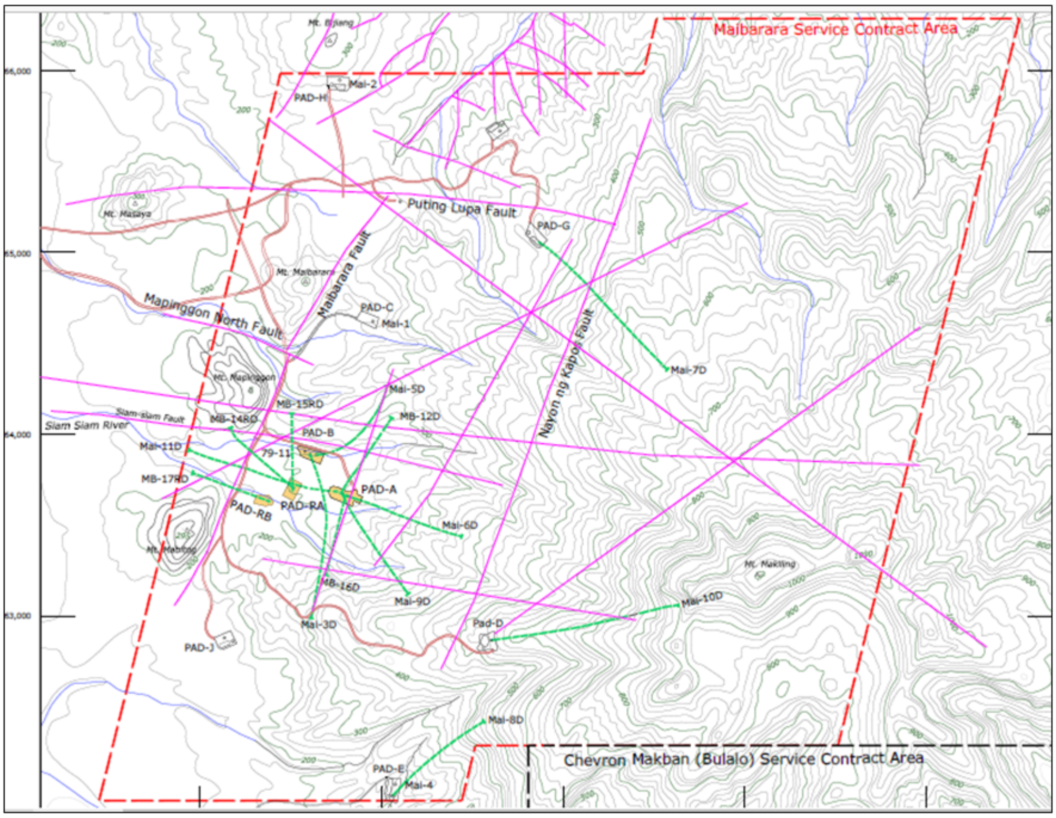

FIGURE 2: Maibarara Service Contract area (information from Maibarara Geothermal Inc.)

In 1974, the Philippine Geothermal Inc. started the exploration at Mt. Makiling, resulting in the drilling of 12 wells in the Maibarara area (Buban et al., 1994). Maibarara Geothermal Inc. developed and reworked the existing three wells in 2011 for use in a 20 MWe commercial power plant unit and since then 5 wells have been added. The production wells tap neutral pH, high chloride and high-temperature (~320°C) fluids from the upflow zone. The production and development of the Maibarara geothermal facility is concentrated within the 2.5 km^2 proven reservoir area. (Maturgo et al., 2015). The well depths range from about 1400 to 2985 meters. Currently, five wells are in use; three production wells (Mai6D, MB-12D and MB-15D) and two reinjection wells (MB-14RD and MB-16RD) as shown in Figure 3.

FIGURE 3: Maibarara geothermal field overview

The power plant is designed for a two-phase, liquid-dominated system, with a single-flash condensing steam turbine manufactured by Fuji Electric. M1GPP is an axial exhaust type geothermal steam turbine with a direct contact type condenser. The gas extraction system is a hybrid type with steam ejector back-up and a draft counter-flow cooling tower.

The 20 MWe M1GPP successfully started its commercial operation in February 2014. In the beginning, all parameters were within the normal design parameters and design limits. However, after about a month of operations, the 20 MWe gross output of the power plant started to decline and decreased to 18.8 MWe by the end of April 2014. Investigations were conducted and one of the observations indicated increasing turbine chamber pressure and decreasing steam flow, which was speculated to be a result of scaling on the turbine blades. One of the consequences of increasing turbine chamber pressure is that the steam flow to the turbine inlet must be increased to compensate for the declining gross output.

The easiest way to assess whether the turbine blades have deposits is by monitoring the steam purity. In order to make sure that the quality of the steam before entering the turbine is clean with minimal impurities it is necessary to monitor the chemical composition of the condensate. For that reason, condensate samples are collected regularly at different points to make sure that the steam quality is within the limits defined by the turbine manufacturer Fuji Electric. Chemical monitoring shows that the steam has a purity of 99.98% before entering the turbine (Maturgo and Fernandez, 2014).

To address the increasing chamber pressure and the scaling, Fuji Electric proposed the installation of a turbine blade washing system, where water is sprayed through the turbine inlet nozzles to remove any solids carried over to prevent them from accumulating on the blades. This system was installed in September 2014, using cooling-tower water as washing fluid and adjusting the frequency of blade washing to lower the chamber pressure and maintain the plant's output. A more detailed discussion on the turbine blade washing system is presented in section 3.2. Despite the installation of the turbine blade washing system, the chamber pressure continued to increase.

Literature indicates that while turbine blade washing can mitigate scaling, it also has detrimental effects to the turbine in the end. According to Thórhallsson (2012), washing should not be done frequently as it causes erosion and is therefore suggested to be done only twice a year.

The objective of this paper is to study the occurrence of scaling deposits on the turbine blades to assess the turbine performance based on the off-design parameters and to find other mitigation methods to address the scaling on M1GPP.

2. RESOURCE CHARACTERIZATION

The Philippines Geothermal Inc (PGI) explored the Maibarara geothermal field from the late 1970s to the early 1980s and drilled 12 wells. After drilling the Mai79-11 and Mai3D wells, the presence of a high-temperature geothermal resource was established. When these two wells were drilled, the suggested upflow of the resource was located at the centre of the contract area. Since then, the drilling of more wells (Mai5D, Mai6D, Mai9D and Mai11D) has proven the existence of a commercially exploitable resource with an aerial extent of 2.5 km^2 and an estimated steam reserve of 700 MWe-yrs (Maturgo et al., 2015).

2.1 Geology

The Maibarara geothermal field is located on the northwestern flank of an extinct andesite stratovolcano, Mt. Makiling (Buban et al., 1994). Mt. Makiling belongs to a group of domes, maars, and volcanoes associated with the northeast trending Macolod Corridor, a 40-80 km wide area of young, intense and active faulting and explosive volcanism. The Macolod Corridor yields an ideal setting for geothermal development (Maturgo et al., 2015).

Makiling volcanic and pre-Makiling volcanic formations underlie the Maibarara wells. The formations are composed of dacite lavas with interlayers of tuffs and andesites. Near the centre of the geothermal resource, a hornblende-quartz diorite pluton intersects the pre-Makiling formation at 2500 m depth. pre-Makiling volcanics host the geothermal resource (Maturgo et al., 2015).

During drilling, several faults were encountered and two major structures were identified: an E-SE oriented fault system and a NE-SW trending fault system. The E-SE fault system includes the Puting Lupa, Mapinggon, Mapinggon North, Mai9, and Siam-siam faults. The NE-SW fault system includes the Bijiang faults and the almost parallel Maibarara, Nayong-Kapos, and Kaplas faults. Subsurface projections of the faults can be connected to identify permeable zones in the wells. The Nayong-Kapos and Maibarara faults form the eastern and western boundary of the reservoir, respectively. Permeability in the field is also associated with lithologic contacts between tuff and andesite layers within the pre-Makiling and Makiling volcanics (Maturgo et al., 2015; Olivar et al., 2011).

2.2 Geochemistry

The Maibarara wells discharge two-phase high-temperature fluids with aquifer temperatures ranging from 300 to 320°C, average enthalpy of 1,900 to 2,100 kJ/kg. The reservoir fluid has neutral pH and a chloride content between 5,000 and 8,000 ppm.

The production wells at Maibarara are Mai-6D, MB-12D, and MB-15D. The Mai-6D has lower CO_2 and H_2S content compared to the other production wells. The NCG (Non-condensable gas) content is about 1.02% by weight before separation. The average Cl concentration at pipeline or wellhead conditions is about 5,000 ppm. MB-12D has higher chloride and gas content compared to Mai-6D with an average of 7,300 ppm Cl and with NCG of 1.69%. The fluid temperature is 310 to 325°C based on silica and sodium/potassium geothermometry. The MB-15D has a chloride concentration of around 6,800 ppm and the highest gas content of 2.18%. The fluid temperature is 297 to 320°C based on silica and sodium/potassium geothermometry (Maturgo and Fernandez, 2019).

2.3 Reservoir characteristics

The Mai1 and Mai2 are the first two wells that were drilled, located in the northern section of the field. They intersected relatively low temperatures of around 190-240°C with reversed temperature profiles that suggests that they are drilled into the outflow of the resource. Good permeability and high reservoir temperature greater than 300°C are encountered in the wells drilled into the centre of the field (Mai3D, Mai5D, Mai6D, Mai9D and Mai11D). Indications of the existence of two-phase fluids in the upflow region were observed during the flow testing of these four wells, which discharge steam-rich fluids with enthalpies ranging from 1500 to 2300 kJ/kg. Wells Mai4 and Mai8D in the south show formation temperature of 290-300°C but have poor permeability (Maturgo et al., 2015).

2.4 Conceptual model

Figure 4 illustrates the hydrogeological model of Maibarara reservoir, based on drilling results. The section shows the tracks of Maibarara wells and the subsurface temperatures. In the field 17 wells have been drilled, 12 of which were drilled in the late 1970s to early 1980s. Wells shown in black are used for field operation while the ones in blue are abandoned wells.

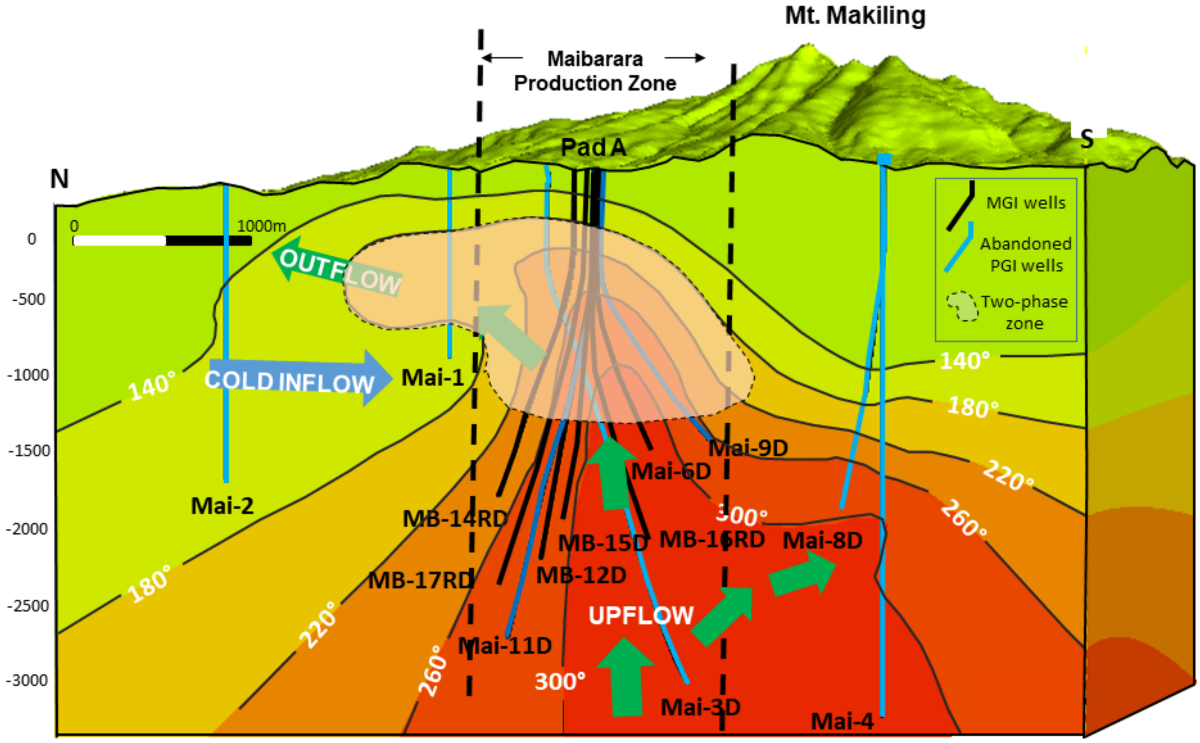

FIGURE 4: Maibarara geothermal conceptual model
(Maturgo et al., 2015)

The production wells tap neutral pH, high chloride, and high-temperature fluids ranging from 300°C to 320°C within the upflow zone. The fluid rises and boils, producing a shallow two-phase horizon at 400 to 1200 m depth. Fluids continue to flow towards the north where they cool, and towards the south where the resource deepens. The location of the most permeable area is between 800 and 1600 m b.sl. (below sea level) mainly due to lateral permeability and faults (Maturgo et al., 2015).

3. OVERVIEW OF MAIBARARA 1

3.1 Operational data

The 20 MWe Maibarara 1 geothermal power plant (M1GPP) started its commercial operation in February 2014. The two production wells (Mai-6D and MB12D) were used to supply steam to the power plant. The steam is separated from the brine with a vertical separator and before the steam enters the plant turbine, a scrubber is installed for the final removal of moisture and carry-over. A schematic steam gathering system is shown in Figure 5.

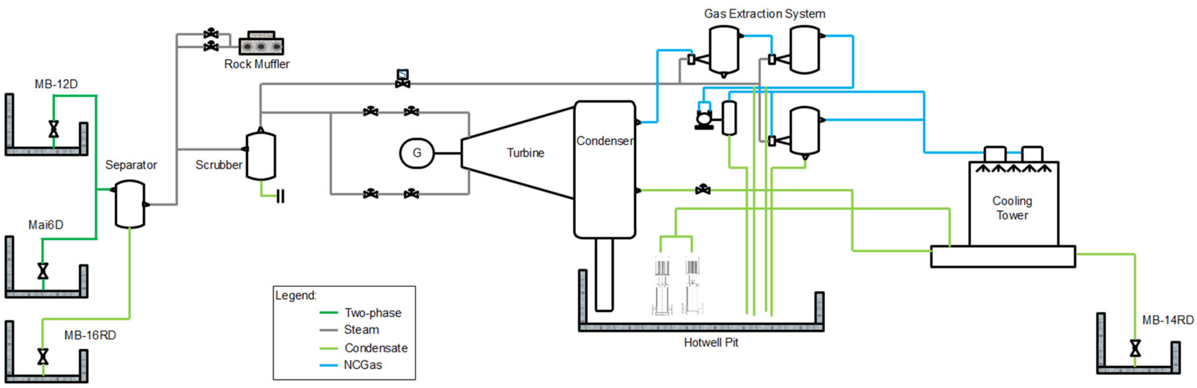

FIGURE 5: Schematic diagram of Maibarara 1

The power plant continuously operated under normal conditions but in April 2014, the maximum capacity had already dropped from 20 MWe (gross) to 18.8 MWe. At the same time, other parameters showing deviations, that is increasing turbine inlet and chamber pressures and decreasing steam flow to the turbine. Figure 6 shows the composite plot of selected plant parameters, illustrating how the inlet and chamber pressures increased from 5.59 and 5.28 bar to 6.51 and 6.30 bar respectively, while the steam flow decreased from 40.2 kg/s to 38.5 kg/s. This suggested a possible narrowing of the steam path between the turbine blades.

At this moment, MGI decided to shut down the unit for one day to conduct visual inspection of the bucket strainers. The initial speculation was that the bucket strainers might be clogged with deposits. However, the inspection revealed that the strainers were clean and free from deposits. The turbine blades were also inspected using a borescope but no scales were seen. The shutdown also presented a chance to open the scrubber for visual inspection, but no deposits were found.

Inspection showed that the bucket strainers and the first and last stage turbine blades were free from deposits. The result of inspection did not seem to support the initial speculation that deposits were causing the decline in plant output. Other parameters which also may cause load decline were scrutinized, such as increasing non-condensable gases and elevated temperature of cooling water. However, the NCG values were below the 2.5% limit and the increases in cooling water temperature led to an increased vacuum pressure. After the inspection, the gross load was expected to reach the design load but unfortunately, the gross load only reached 18.2 MWe. To achieve the required gross output,

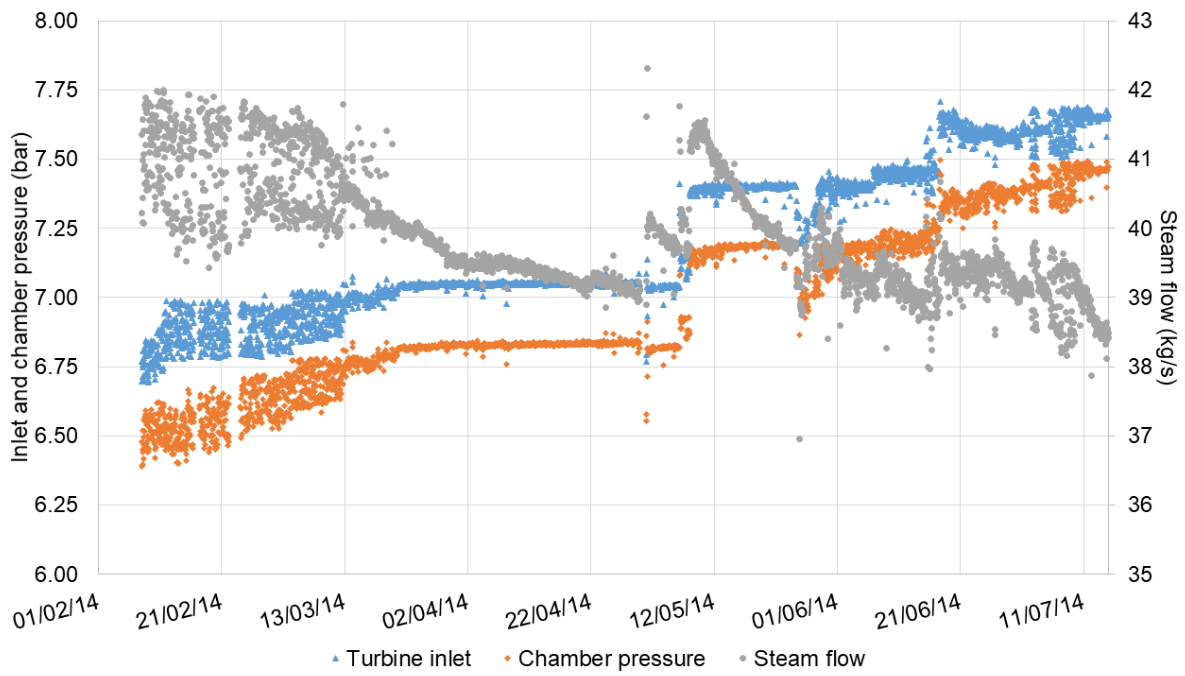

FIGURE 6: Composite plot of power plant parameters

the turbine inlet pressure was increased to 6.28 bar, with the approval of the turbine manufacturer. However, the steam flow also declined with the power output still below 20 MWe. Figure 7 shows the steam flow decline to 38.1 kg/s, and the corresponding decline of gross power output to 18.0 MWe.

Further analysis was conducted to determine the possible causes of the decreasing gross output. Two additional causes were suggested: Firstly, the possible occurrence of scales/deposits on the turbine and secondly, a problem with the vacuum which might be caused by the cooling water system. Based on the evaluation of the actual plant parameters, the chamber pressure corresponding to chamber pressure ratio had been increasing since commercial operations started. The chamber pressure ratio is the ratio

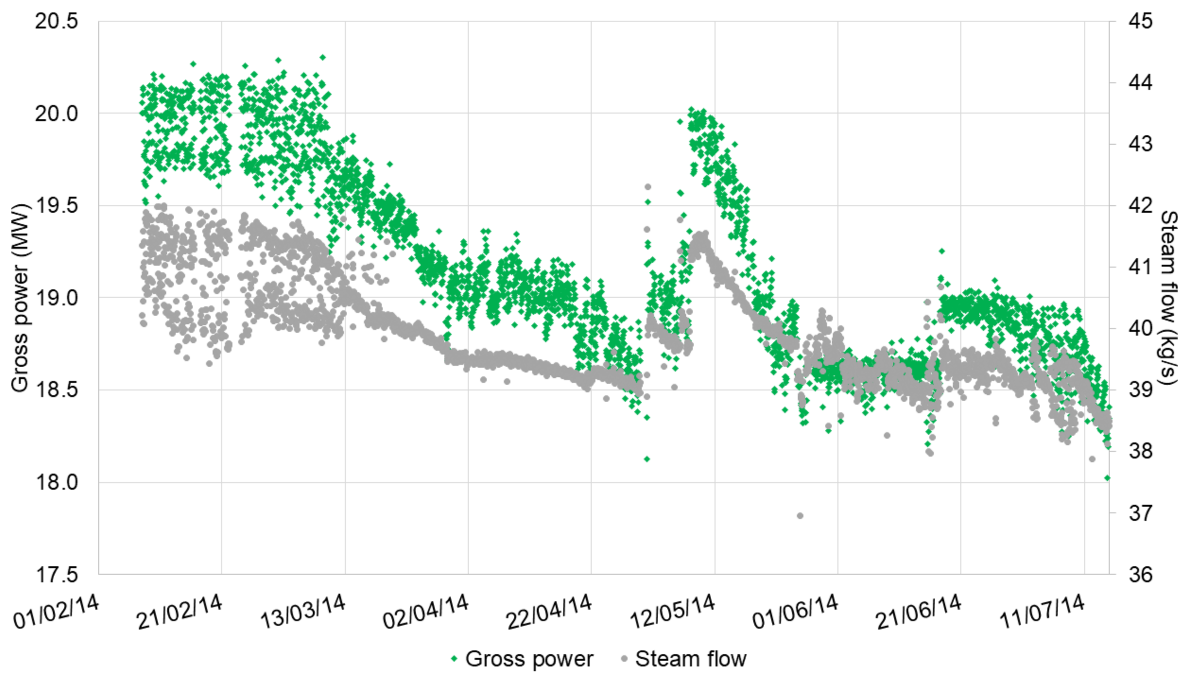

FIGURE 7: Plot of steam inflow and power plant output

of the turbine chamber pressure to the exhaust pressure. It is a parameter that is used to determine narrowing of the steam path or the possible accumulation of scaling on the turbine blades.

Figure 8 compares the decline of gross power output with the increasing chamber pressure ratio. Based on the experience of Fuji Electric, increases in the chamber pressure ratio are normally caused by deposition on the turbine blades. Fuji Electric therefore recommended the installation of a turbine blade washing system at MGPP to address the formation of deposits on turbine blades. At the time, the only turbine inspection was carried out using a borescope, which has limited visual access. The only parts inspected were the upper section of the turbine blades, but not the bottom parts where deposits could possibly be forming. Before the inspection in July 2014 the chamber pressure ratio had reached 39.3% and the gross load decreased to 18.0 MWe.

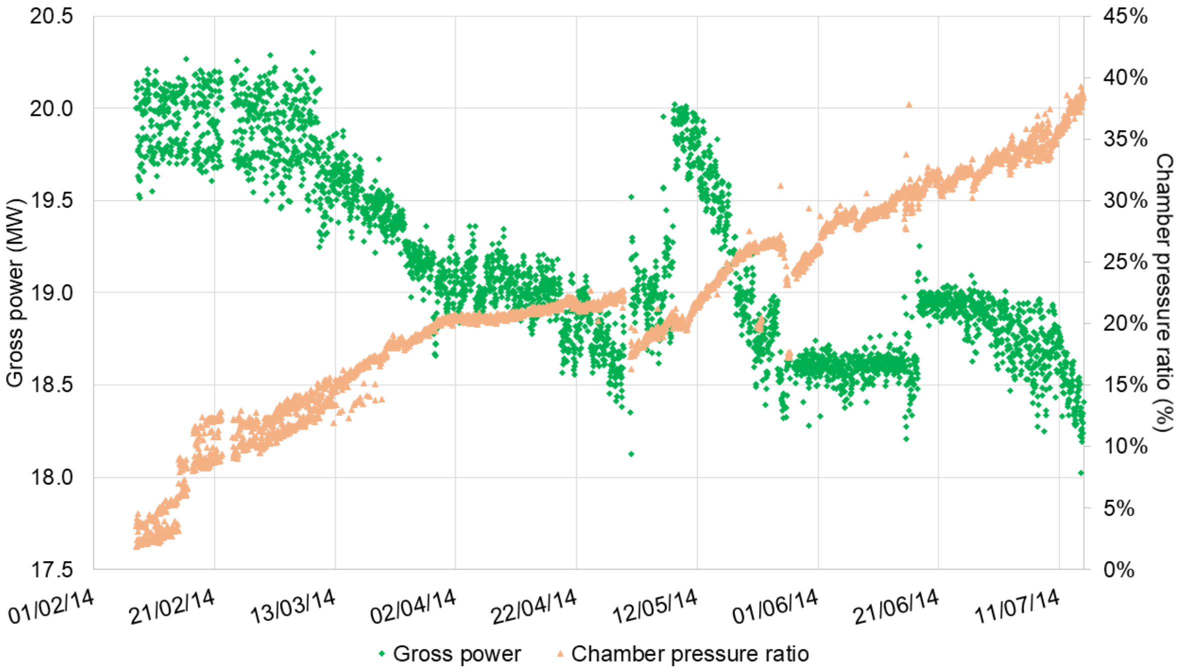

FIGURE 8: Plot of gross output and chamber ratio

The abnormality in the turbine performance lead to an early turbine overhaul to determine and to confirm the speculated scaling in the turbine. The first turbine overhaul was conducted in July 2014 and the inspection showed that the turbine displayed corrosion of the turbine blades and deposits of iron sulphides. The scaling deposits are formed mainly in the first stage of turbine blades. Inspection also presented an opportunity to install a turbine blade washing system as proposed by Fuji Electric to address the scaling issues.

3.2 On-line turbine blade washing

If geothermal steam contains impurities, they may cause scaling deposits along the steam path such as on the turbine blades. If scaling occurs on the blade surface, the blade channel area decreases and the inlet pressure rises, assuming the steam flow through the blade channels remains constant. And, if the blade inlet pressure cannot be further increased, which is the case if the steam control valves are already fully opened, the inlet steam flow decreases resulting in power output deterioration.

When the blades are clean, there is a nearly linear relationship between the steam flow through the blades and the chamber steam pressure. However, this relationship changes when scales have formed on the surface of the blades and narrowed the steam passage through the blades, and the pressure rises.

Therefore, when the wheel chamber pressure rises against the steam flow, it is necessary to check the steam purity. One countermeasure used to address the scaling in the turbine blades is to use on-line blade washing, where a washing fluid is used to clean deposition from the blades.

A turbine blade washing system was installed and the supply water led into the wash water piping, which was branched off from the hot well pit discharge piping and pressurized through the turbine washing pump. The composition of the washing fluid is the same as that of the cooling towers, i.e., steam condensate to which has been added a soda ash (Na_2CO_3) solution for pH adjustment. Wash fluid flow is controlled to be about 0.5-2.0 wt.% of the main steam-flow by the control valve. The washing operations take two hours.

The on-line blade washing is performed during normal operations to remove the scales and to recover the output. Based on the M1GPP operation and maintenance manual, if the chamber pressure rises 10% above the normal chamber pressure at the corresponding steam flow, blade washing is recommended to be performed. If the scales on the blade are washed out the chamber pressure should be reduced.

The operation of turbine blade washing was commissioned in September 2014. The turbine chamber pressure ratio before the washing was 14.19% and after the washing the ratio decreased to 9.8%. This shows that the turbine blade washing effectiveness is almost 5%. As stated in the operation and maintenance manual the turbine blade washing is recommended when the limit value of 10% is reached.

The two years historical data of turbine blade washing performance is shown in Figure 9, presenting the chamber pressure ratio before (blue) and after (red) each washing event. The figure shows that despite frequent washing the chamber pressure ratio still shows an increasing trend.

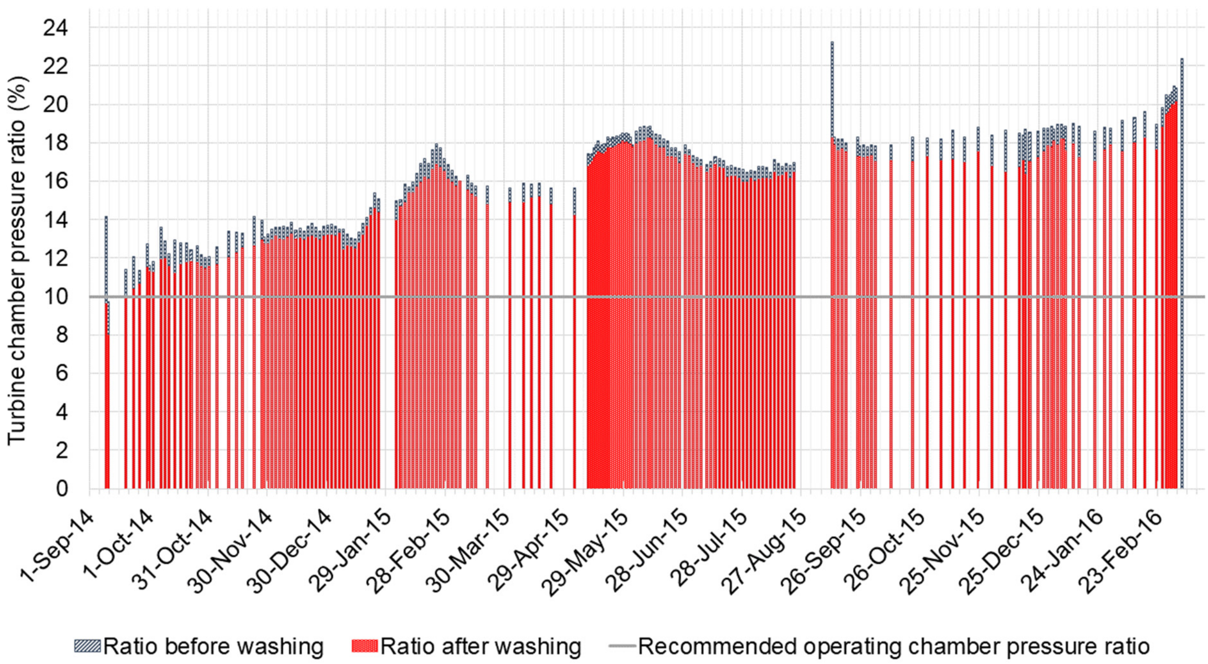

FIGURE 9: Historical turbine blade washing data

The constantly increasing chamber pressure indicates that deposition on the turbine blades is still present. Moreover, the issue of the scaling is not yet solved, even though the turbine blade washing system is in continuous operation. To confirm scaling on the turbine blades, inspection of the turbine is necessary. Turbine inspection was scheduled parallel to a major overhaul for preventive maintenance in March 2016. Before the maintenance break the chamber ratio reached 22.39% after two years of operation with turbine blade washing.

3.3 Turbine inspection

The inspection of the turbine is necessary to determine the presence of deposition on the turbine blades and the cause of the increasing trend of the chamber pressure ratio. The inspection will determine the effectiveness of the blade washing, how the blade washing system helps to remove the scaling in the turbine and the comparison of the turbine with the 2014 inspection. During a major preventive maintenance overhaul, scheduled in March 2016, the planned activities included checking solids on turbine blades, cleaning the main cooling system (cooling tower and tower basin) to address issues in cooling system and a major overhaul of auxiliary equipment.

The second inspection of the turbine revealed powdery white scales in the labyrinth steam seals. On the upper part of the first stage, the stationary blade had thick, hard deposits on its trailing edge. Deposits on the upper and lower stationary blades were observed in the first stage, mostly on the trailing edge of the blades. It was also noted that the first stage upper stationary blade had thicker deposits compared to the first stage lower stationary blade.

The moving blades were generally clean and very limited deposits, identified as corrosion products, were collected from the fourth and fifth rotating blades**.** The first stage moving blades, where pitting was observed, also had deposits while no significant erosion was observed on the stellites installed on the seventh stage blades. There were none or minimal deposits on the other blades.

The inspection results in 2016 were different from those observed in 2014 when iron or corrosion materials were found in the turbine. The iron deposits may possibly have resulted from insufficient insulation and back-heating along the power plant main steam line during pre-commissioning activities, promoting steam condensation, inefficient steam/condensate traps along the power plant's main steam line and lack of dry preservation of the turbine during the commissioning period.

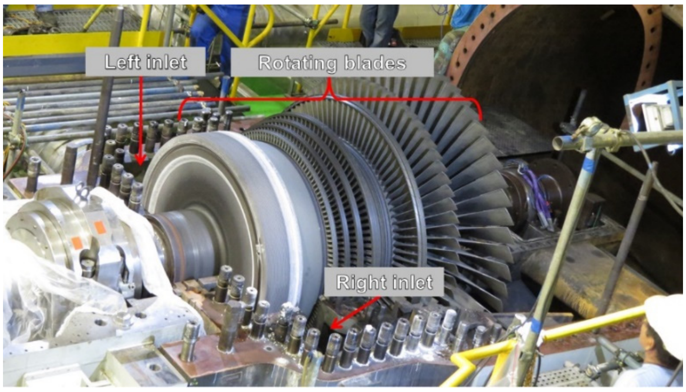

FIGURE 10: Turbine rotating blades

To determine the chemical composition of deposits, samples were collected from the different parts of the turbine. Then sand blasting was used to remove the scaling deposits in the turbine. Figures 10-14 show the actual condition of turbine blades during the major overhaul preventive maintenance in 2016.

FIGURE 11: Upper half of stationary blades

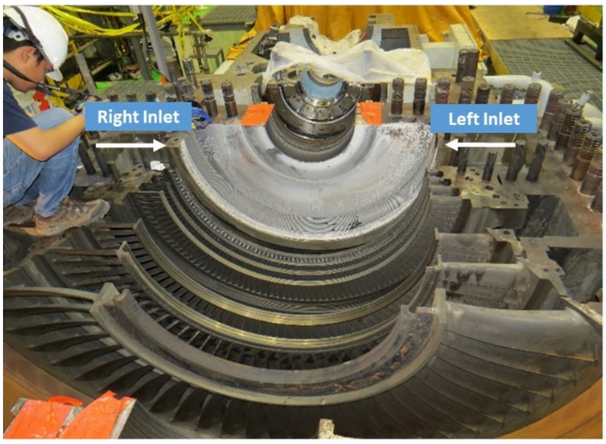

FIGURE 12: Lower half of stationary blades

FIGURE 13: Close up view of the 1st stage upper stationary blades (trailing edge)

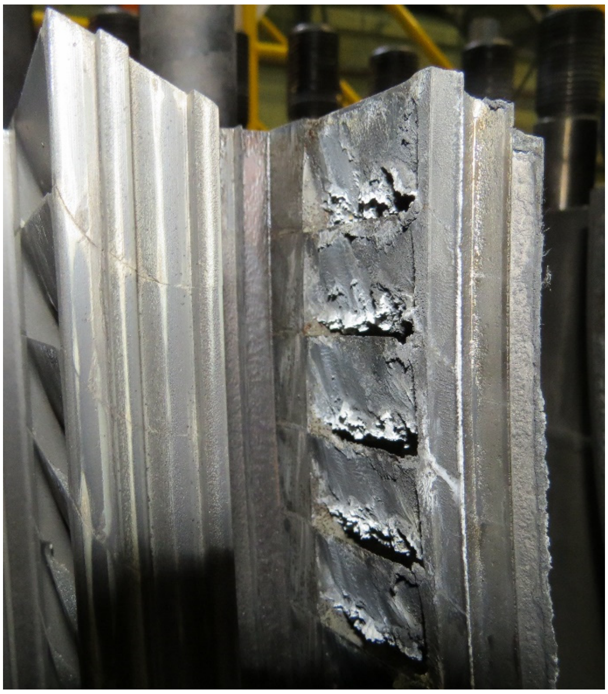

FIGURE 14: Close up view of the 1st stage lower stationary blades (trailing edge)

3.4 Samples result

The scaling deposits in the turbine were analysed to figure out their source and to solve the problem. These deposits became the number one suspects of the increasing chamber pressure and load deterioration. Further investigations were carried out to figure out the origin of the deposit.

Deposit samples were collected from the turbine blades for compositional analysis using X-Ray Fluorescence (XRF) and X-Ray Diffraction (XRD). Inherent components of geothermal brine are elements like Cl, Na, K and SiO_2; a small amount of these may be carried over in the steam after flashing at the separator vessel. If sufficient amounts of such carry-over components enter the turbine where the water droplets evaporate, over time some amounts of evaporation products such as calcite and sodium chloride may build up as deposition on the blades.

Table 1 lists the XRF and XRD results for samples collected in March 2016. XRD gives the compound or mineral phase composition of the sample while the XRF gives the elemental composition. The results from XRD shows that sodium chloride is the most dominant compound present in the scaling deposits, whereas the XRF results shows the presence of iron suggesting the possible formation of iron sulphide in the piping. Because of the limitations of the instrument used for XRF, there are no results for the light elements from hydrogen (H) to sodium (Na), and therefore no sodium is reported in the elemental composition.

The deposits show the possibility of brine carry-over in the steam that may be transported in droplets that evaporate when they reach the turbine, leaving evaporates such as NaCl and $CaCO_3$. In order to determine the origin of the scales in turbine, steam purity and steam condensation should be assessed.

TABLE 1: Turbine samples XRF and XRD results

Sample	Fluid type	Approx. mass of sample	XRD Results	XRF results (elemental composition)	
Labyrinth rotating blades (front/powder)	Steam	5 g	Sodium chloride	Cl (67.1%), S (11.2%), Fe (9.1%), K (9.5%)	Ca, Mn, Cu, Se, As, Sr, Cr
Labyrinth seal upper casing	Steam	5 g	Sodium chloride	Cl (59%), S (18.8%), K (12.3%), Ca (6.1%)	Fe, Si, Mn, Cu, Zn, As, Sr
Right wall / 4th stationary blades	Steam	<5 g	Magnetite, iron sulphide	Fe (80.2%), S (13.9%)	Mn, Al, Cu, Zn, Se, As, Cr
1st stage stationary blades	Steam	5 g	Calcite, calcium sulphate	Ca (61.9%), Fe (17.1%), Si (7.2%), Cl (5.5%), K (5.9%), S (5.0%)	Mn, Cu, Zn, As, Sr, Cr
5th stage rotating blades	Steam	<5 g	Sodium sulphate, sodium chloride	Fe (46.6%), S (26.1%), Cl (15.5%)	Si, Ca, K, Mn, Cu, Zn, Se, As, Cr

4. ANALYTICAL METHODOLOGY

After five years of M1GPP operations, the scaling depositions are still accumulating despite the frequent turbine blade washing operations. It seems that the problem encountered during the first year of operations is still cause for concern in the generating units. To determine the possible causes and how the scaling deposits formed in the turbine, chemical analysis of condensate and the assessment of steam purity are needed to compare to the deposit samples collected during the last inspection of the turbine (2016). Assessment of turbine performance is based on off-design parameters using the daily data collected in the Distributed control systems (DCS). The data that will be used was collected after a major overhaul of the turbine, improvement of the cooling water systems and modification of the piping line, during the 2016 shutdown. In this case it is assumed that the power plant performs according to its design parameters.

4.1 Scaling in geothermal equipment

Scaling by mineral deposition is a common problem in geothermal utilization, it occurs on all surfaces in contact with the brine component. Different types of geothermal fluids from different wells have brine with differing chemical composition. Contaminants carried by the steam into the turbine can be either chemically aggressive or non-aggressive. Aggressive compounds considerably influence the extent to which the steam path deteriorates in terms of its structural integrity. Both can influence the efficiency with which the steam expands through the unit. There are two major concerns with steam-borne contaminants: reduction of efficiency due to surface deterioration of the steam path elements and any resulting frictional losses that occur, and the reduction in structural integrity resulting from corrosive action on the various components of the unit.

The scaling conditions are constantly changing as the geothermal fluid travels from the wells and through the pipelines and back to the reservoir due to ever changing temperatures, pressure and composition of the two phases. This makes scaling prediction somewhat uncertain but by coupling chemical modelling calculations, pilot studies and practical experience it has usually been possible to come up with solutions that overcome the most serious scaling problems. To monitor the scaling or corrosion at various locations in the pipelines it is possible to install retractable metal coupons that can be removed for periodic inspection without affecting the flow or operation of the plant.

4.1.1 Steam Purity

Van der Mast et al. (1986) discussed that in geothermal utilization from both liquid-dominated and vapour-dominated geothermal resources, poor steam purity can cause long-term effects in economic terms and in the reliability of a geothermal power plant. Most impurities found in geothermal steam are silica, chloride, sodium, carbon dioxide, hydrogen sulphide and corrosion products. Among the impurities that can cause problem in geothermal utilization integrity and reliability are silica, sodium chloride and hydrogen sulphide.

Saunders (2001) determined that the compound deposition that occurs on the turbine blades are composed of two different types: compounds insoluble in water, which can only be removed by mechanical means and soluble compounds that can be removed by immersion or washing by water.

Richardson et al., (2013) state that the presence of chloride and sodium in steam can cause corrosion in piping, vessels and turbine. Chloride can easily be evaporated at normal temperature while sodium in steam evaporates due to pressure changes resulting from the brine carry-over. Sodium chloride and sodium hydroxide deposits are commonly found in turbines and are corrosive agents that might affect the steam turbine path. These deposits can break off the blade and cause foreign object damage (FOD) to the turbine blades and parts.

Saunders (2001) explains that the presence of caustic contaminants in the steam phase can attribute to the ingress of common salt (NaCl) into the system. Separation of common salt into sodium (Na^+) and chloride (Cl^-) ions then recombines with hydroxide (OH^-) and hydrogen (H^+) ions to form caustic sodium hydroxide (NaOH) and hydrochloric acid (HCl).

Monitoring of steam purity is necessary before the steam enters the turbine to determine if the steam purity is within the recommended limits of the turbine manufacturer. Table 2 shows the recommended

TABLE 2: Recommended values and limit values for steam purity from Fuji Electric

Parameters	Recommended values	Limit values
pH (at 25°C)	$5.0 \leq pH \leq 10.0$	$4.0 \leq pH \leq 10.0$
Steam wetness	≤ 0.02%	≤ 0.1%
Total dissolved solids (TDS)	≤ 0.5 ppm	≤ 5 ppm
Suspended solids (SS)	≤ 0.1 ppm	≤ 1 ppm
Chloride ions (Cl^-)	≤ 0.1 ppm	≤ 1 ppm
Sulphate ions (SO_4^{2-})	≤ 0.1 ppm	≤ 1 ppm
Sodium ions (Na^+)	≤ 0.1 ppm	≤ 1 ppm
Potassium ions (K^+)	≤ 0.1 ppm	≤ 1 ppm
Calcium ions (Ca^{2+})	≤ 0.1 ppm	≤ 1 ppm
Fluoride ions (F^-)	≤ 0.1 ppm	≤ 1 ppm
Arsenic (As)	≤ 0.1 ppm	≤ 1 ppm
Boron (B)	≤ 0.5 ppm	≤ 5 ppm
Silica (SiO2)	≤ 0.1 ppm	≤ 1 ppm
Total Iron (Fe)	≤ 0.1 ppm	≤ 1 ppm

values and limit values for steam purity at turbine inlet provided by Fuji Electric. The consideration of such limits is required to provide sufficient steam purity to prevent deposits, scaling, or corrosive materials in turbines.

At M1GPP the steam purity is closely monitored by collecting samples at different locations. Additionally, monitoring of separator water, steam condensation in the pipelines, and the scrubber efficiency are important to make sure that the steam entering the turbine is clean and will not lead to formation of deposits. Figure 15 gives an overview of the Maibarara geothermal field, showing the location of sampling points and the drain pots for steam condensation along the pipelines.

FIGURE 15: Location of equipment and drain pots

Maibarara 1 used isokinetic sampling points (ISK) to capture steam and other particles that pass through a defined area for a defined time without disturbing their paths. To confirm the steam purity of the system three ISKs are installed where condensate and gas samples are collected. ISK 1 is located right after the separator, ISK 2 is located before DP5 (drain pot), and ISK 3 is situated right after the scrubber prior to the entry of the turbine.

Figure 16-19 are plots of selected steam condensate components, which are regularly monitored to determine steam quality, i.e. the purity of the steam. Based on the values below the solute concentrations in steam condensate are within the limits defined by the turbine manufacturer, however they are frequently close to or even above the recommended limits.

Even though the steam purity is within the limits, the power plant still encountered problems in turbine performance. In order to determine the source of the problems, the XRD results for the scaling deposits are compared to the chemical composition of separated brine and steam condensate. Based on the XRD results, the bulk of the scaling is sodium chloride, which is most likely formed by the evaporation of droplets containing sodium, chloride and other constituents. Moreover, this could be formed either from carry-over droplets in the steam, or from the turbine blade washing fluids.

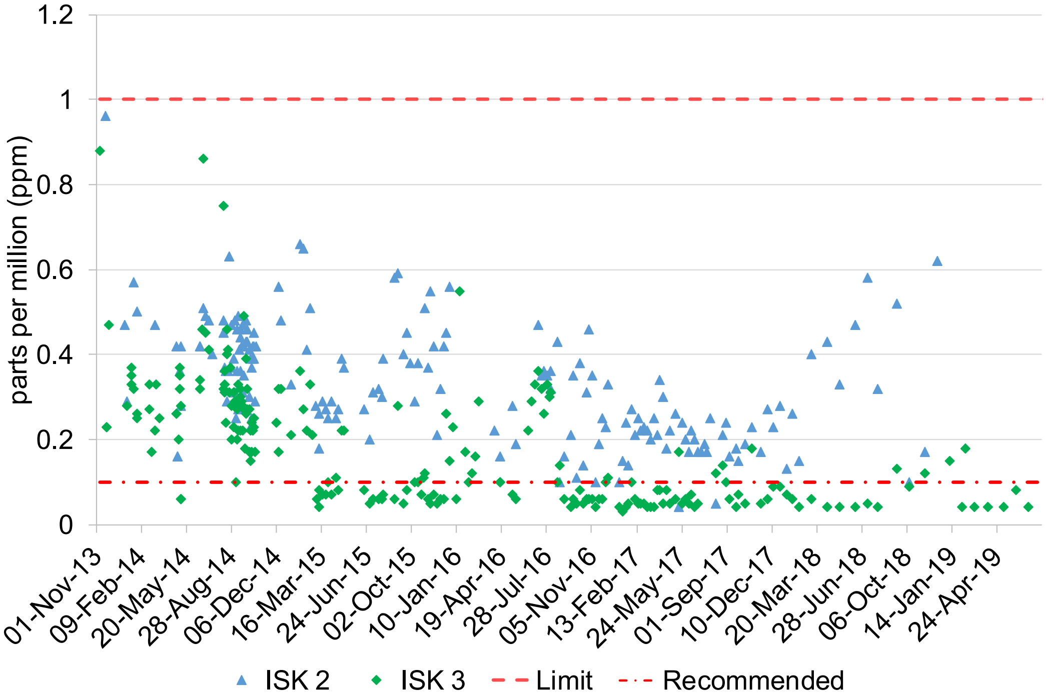

FIGURE 16: Chloride in steam condensate

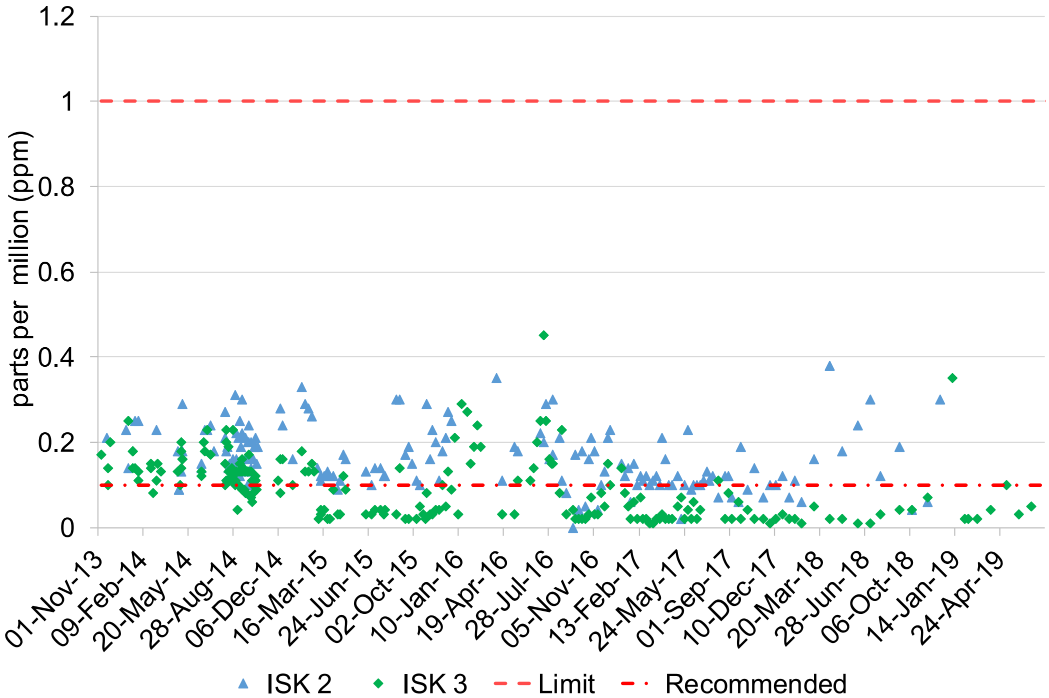

FIGURE 17: Sodium in steam condensate

4.1.2 Steam separation and condensation in the pipeline

Although the steam is transmitted from separators to the steam turbine through insulated pipelines, heat losses and steam condensation occur. Many of the non-volatile constituents carried with the steam will preferentially partition into the condensate as it is formed in the pipeline. To remove condensate that accumulates in the steam line and thus improve the steam purity, a series of drain pots are installed.

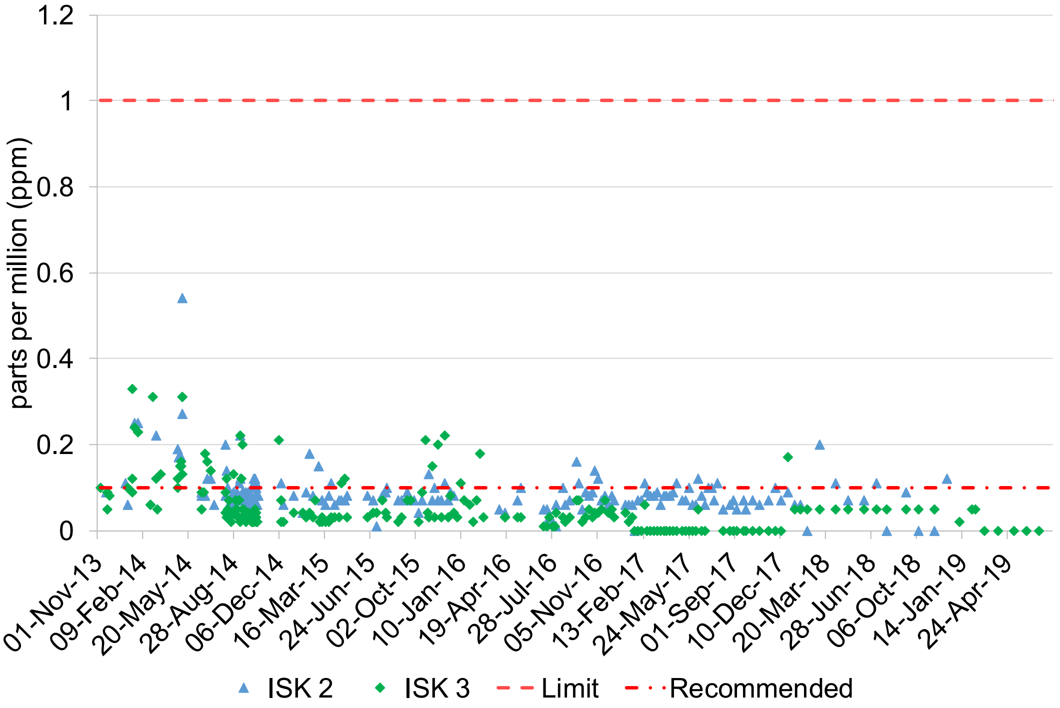

FIGURE 18: Silica in steam condensate

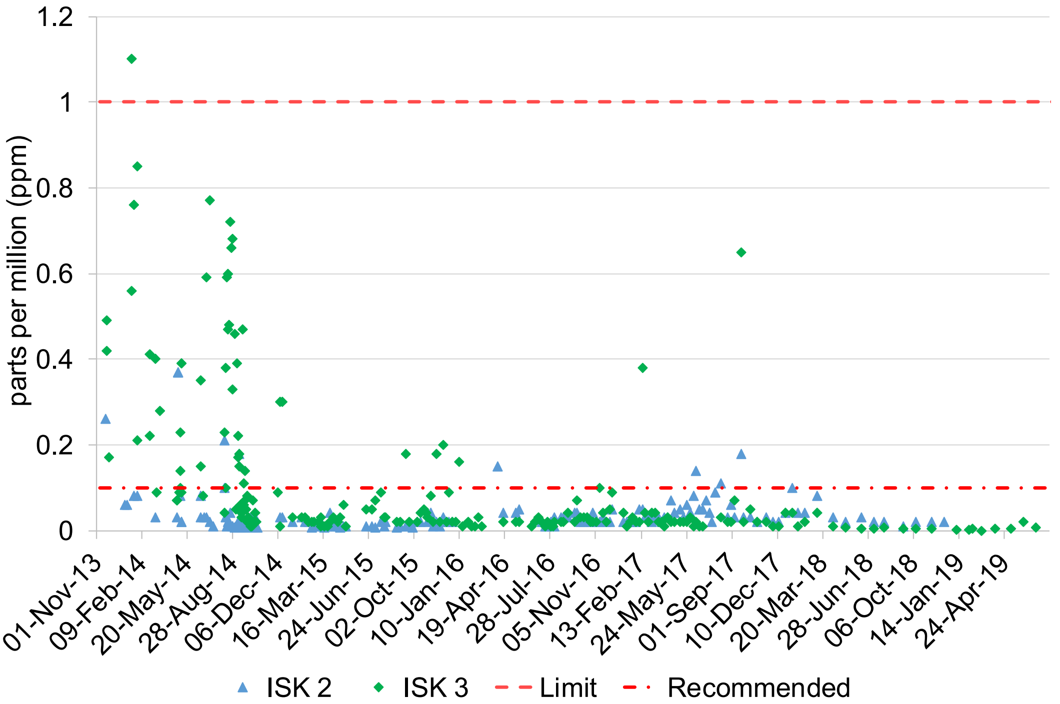

FIGURE 19: Iron in steam condensate

Generally, more condensate is expected to form in longer steam lines or scrubbing lines between separators and geothermal power plants than in the shorter steam pipes at power plants where the steam separators are located at the power plant.

James (1986) discussed that as the steam flows in a pipeline, a dilution of solute concentrations in the liquid phase takes place because of the steady condensate generation along the line. The solutes carried over from brine at the separator may inhibit corrosion within the pipeline but most of these solutes need to be removed before entering the turbine as they may cause deposition of solids on turbine blades and nozzles. It is also important to determine the exact amount of liquid and solutes which moves along the pipeline with the steam and how efficiently these quantities are removed by drain pots located at intervals along the line.

4.2 Turbine off-design performance

Steam turbines in geothermal power plants are designed for stable operation settings. In these conditions, the turbine is expected and supposed to perform at its maximum efficiency. A steam turbine does not always operate at design conditions because of differences in power demand and other turbine issues. Performance at those off-design conditions affects the generation and the economy of the power plant operations. Hence, prediction of performance at off-design conditions is necessary.

It is necessary to consider not only the basic equations of thermodynamics but also the different behaviour of each equipment section for the simulation of a steam power plant's behaviour. The proposed simulation methodologies of Craig and Cox (1970) for steam turbine modelling, which require a great deal of detailed design information and extensive calculations, are not well suited for the purposes of this work because they are not practical for whole system simulation studies. In this section, we study the connection of scaling issues and turbine performance, particularly to off-design parameters.

According to Murugan and Subbarao (2007), it is appropriate to study the external and internal characteristics of the turbine to determine the steam turbine off-design performance characteristics. The turbine external characteristics refer to the flow passing ability of the turbine's operating conditions. Moreover, to determine the off-design performance, three conditions should be specifically considered, i.e. varying steam flow rate, varying condenser pressure and varying inlet steam parameters.

In this section, two different scenarios, with or without turbine washing, are analysed based on the actual parameters/data collected from the daily log sheet of the M1GPP. These scenarios are related to the turbine blade washing system operations to check whether the parameters with or without washing are in off-design performance. The scaling is assumed to affect the steam flow path through what we called "choking". To confirm whether the turbine performance is still working in its design or off-design parameters. As stated above, to determine the off-design performance it is necessary to know the steam flow rate, chamber pressure and the condenser pressure.

Two periods are used here for the simulation of turbine performance. These periods are with turbine blade washing and without blade washing. Figures 20 to 25 show the comparison of parameters for the two different operation periods: two months after major overhaul and without washing and one year after overhaul with turbine blade washing. Based on the chamber pressure the trend for the case without washing shows that the pressure is continuously increasing while with washing the trend is decreasing, maybe because during this period turbine blade washing removes the scaling leading to a wider steam path. In this period, the washing takes place approximately every two to three days. However, the chamber pressure shows a different trend. The steam flow is decreasing. The blue dots are original measurements and the red dots represent a 12-hour moving average of the original measurement data.

Another way to determine the off-design performance is by viewing it in terms of choking in the steam path. Cooke (1983) investigated the off-design performance of a multistage turbine based on uncontrolled and controlled expansion. He used Stodola's cone law or the ellipse law. Based on his study, the turbine flow characteristics are necessary to determine the turbine performance, which corresponds to the expansion through a single nozzle indicating where choke or under-choked flow conditions are present inside the turbine.

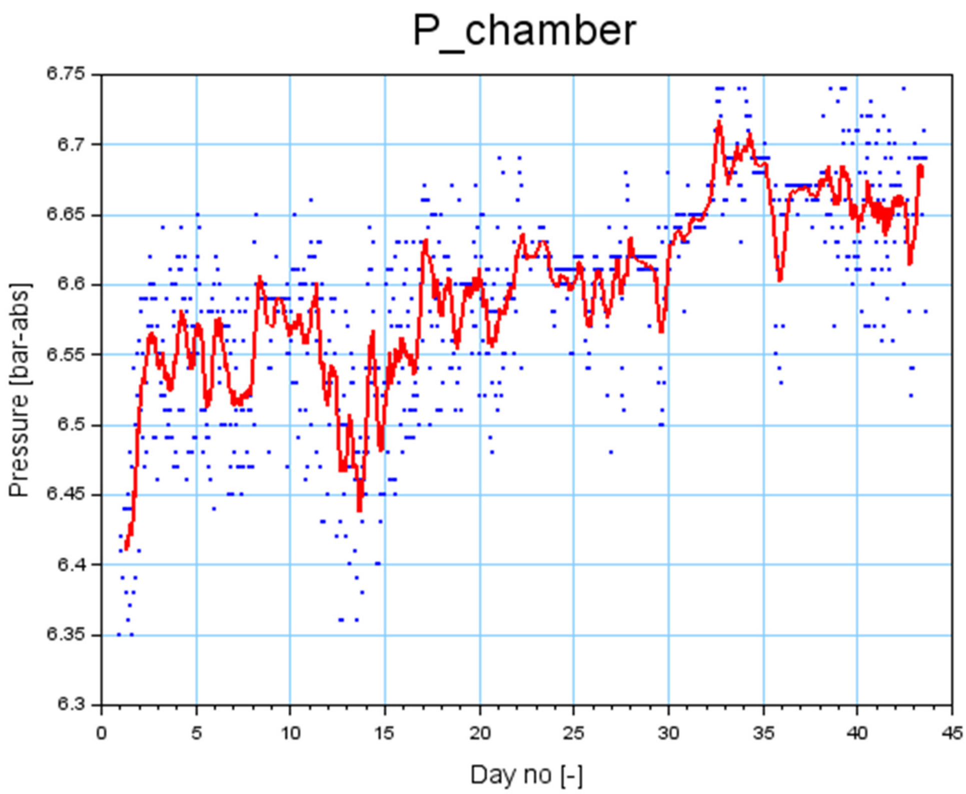

FIGURE 20: Chamber pressure without washing

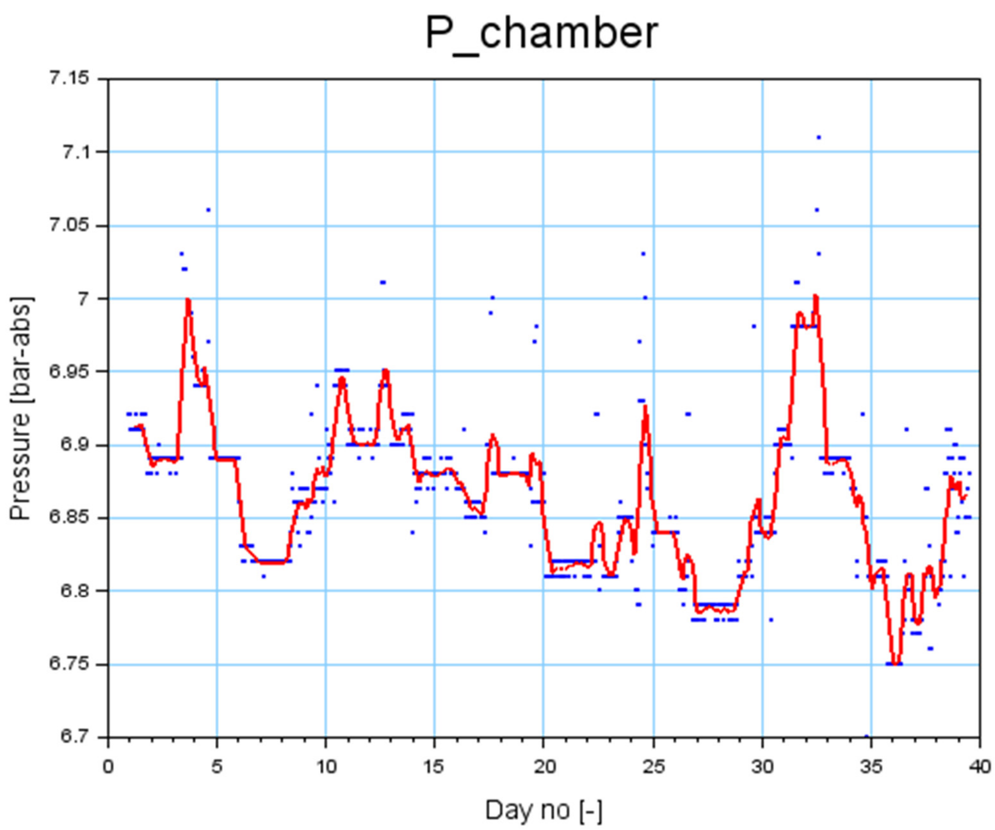

FIGURE 21 Chamber pressure with washing

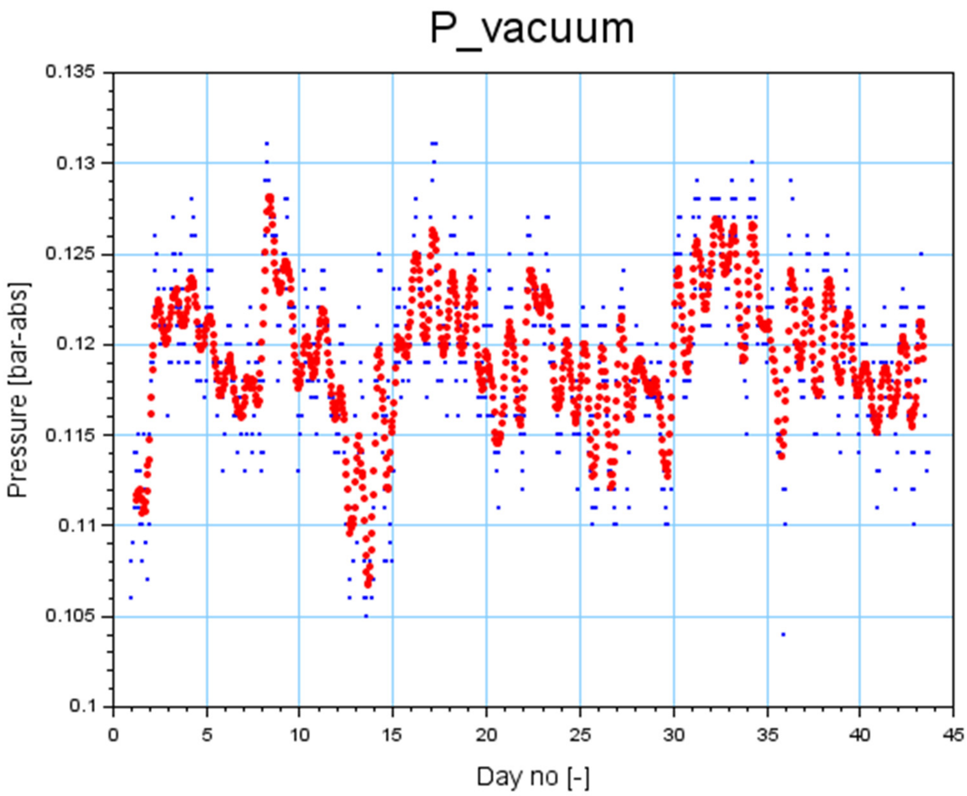

FIGURE 22: Vacuum pressure without washing

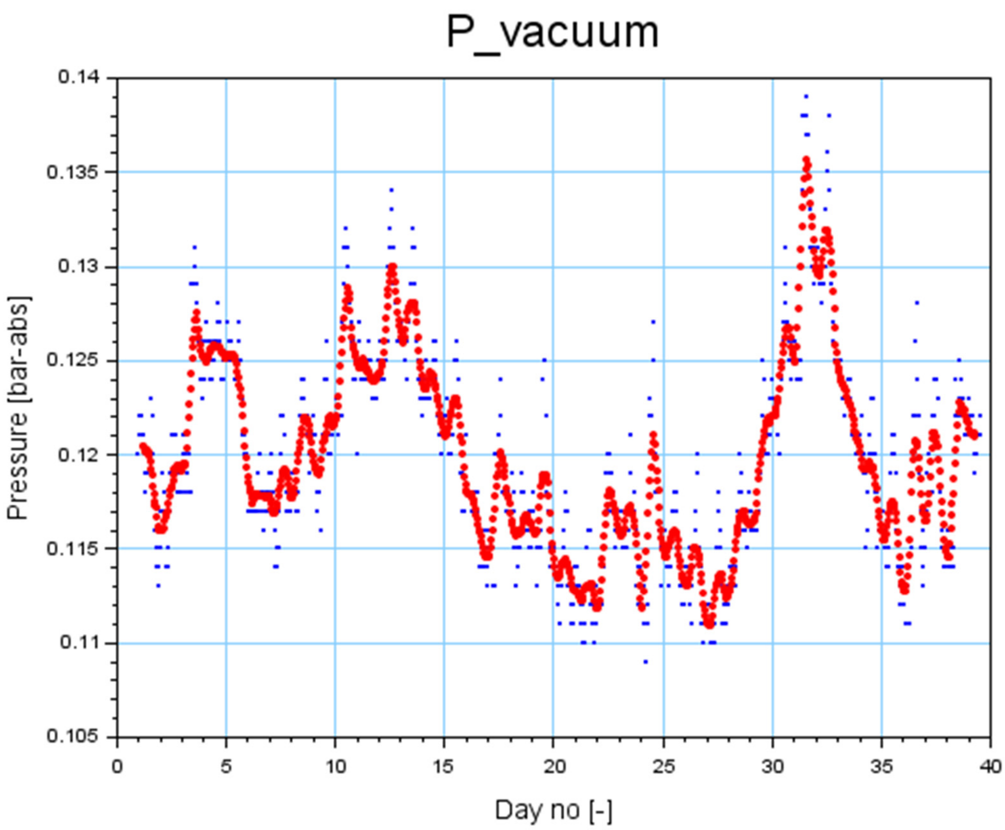

FIGURE 23 Vacuum pressure with washing

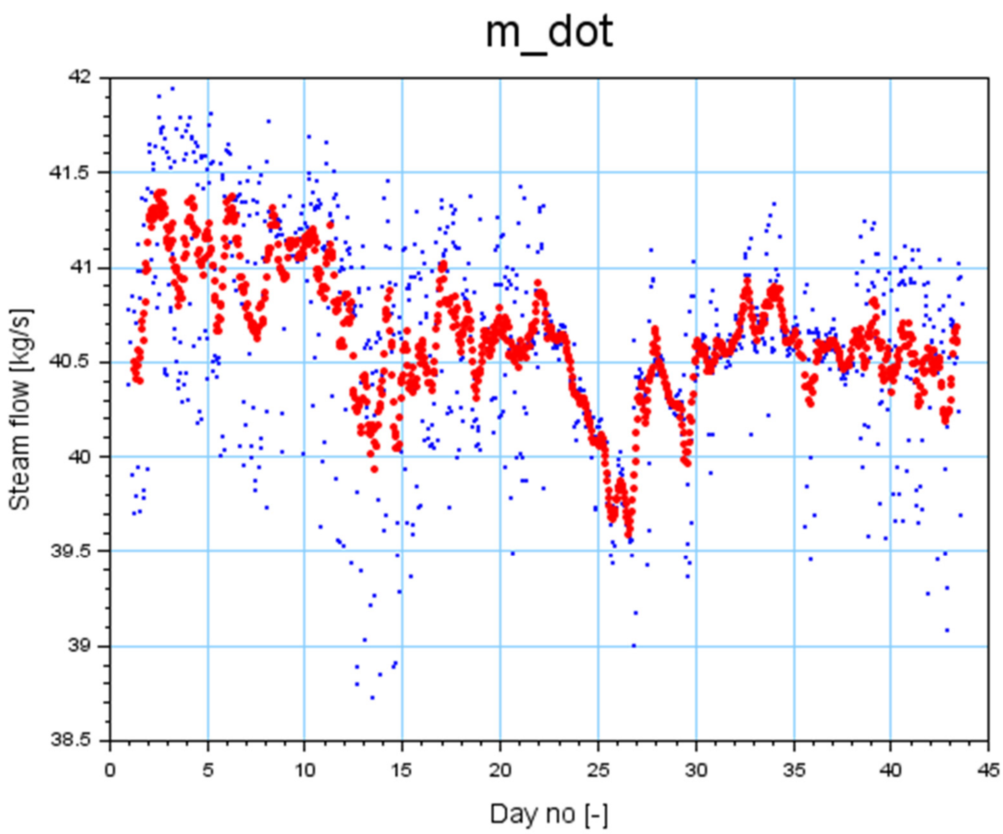

FIGURE 24: Mass flow without washing

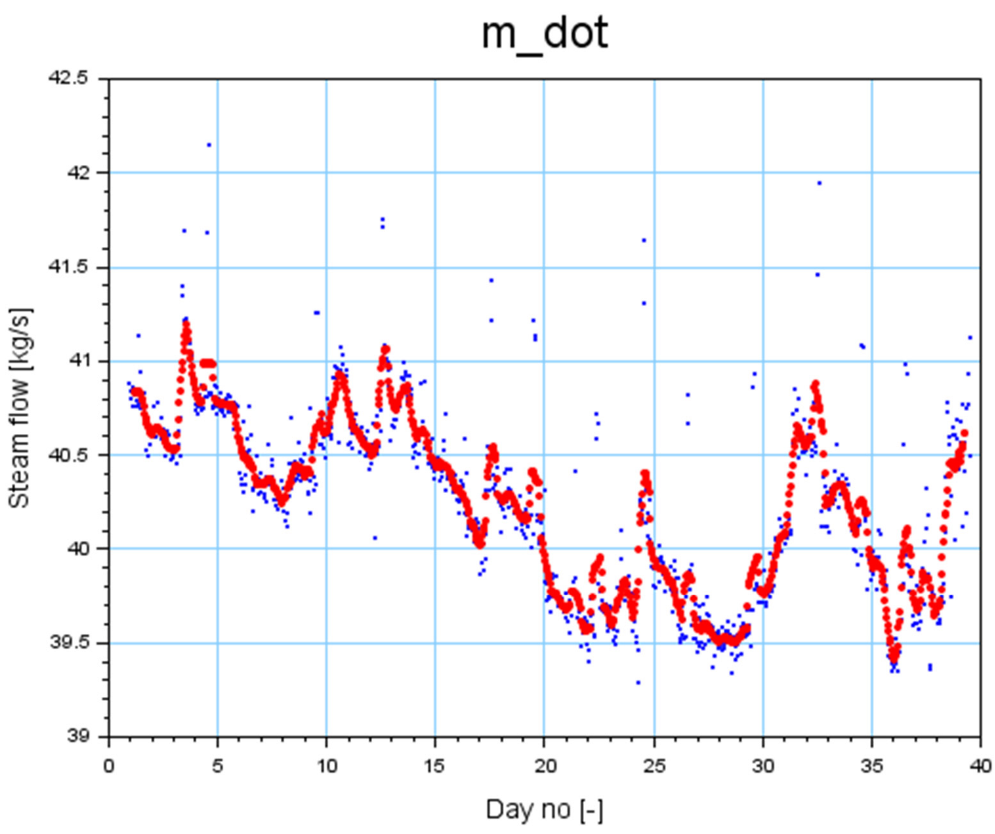

FIGURE 25 Mass flow with washing

4.2.1 Stodola's cone law or ellipse law

Figure 26 shows the behaviour of a multistage turbine section. This is based on the Stodola (1927) study of the variation of the general properties of steam at different pressures and temperatures at the entry of different turbine sections with respect to the pressure ratios and mass flow rate passing through the turbine. Part "a" of the figure corresponds to an operating mode where the outlet pressure is relatively low and inlet pressure is high, while the turbine is operating at supercritical conditions. Under the conditions represented in part "b" the inlet and outlet pressure are the same and the mass flow rate in this case is zero. In case "c", the inlet pressure is constant, and the outlet pressure determines the steam mass flow rate expanded in the turbine section. Then finally in case "d", the outlet pressure is kept constant and the inlet pressure determines the steam flow rate.

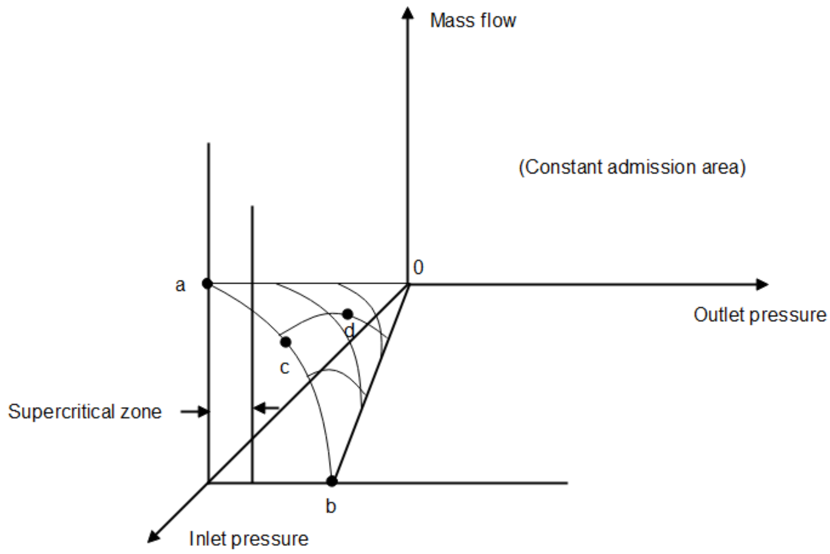

FIGURE 26: Stodola's cone law

Stodola and Lowenstein (1927) obtained an empirical relationship between the pressure ratio P_2/P_1 (P_1 is the turbine inlet pressure and P_2 the turbine outlet pressure) and the mass flow rate $\dot{m}$, with a constant k which is always constant when the flow is not choked:

$$\dot{m} = k\sqrt{1-\left(\frac{P_2}{P_1}\right)^2} \tag{1}$$

This equation is useful for analysing the effect of the pressure ratio on the performance of groups or stages. According to Eustics et al. (1987), this equation cannot be used for general off-design performance analysis since it does not consider the effects of varying initial temperature or the effects of changes in initial pressure when the pressure ratio is held constant.

An alternative form of the cone law was suggested by Silvestri and Martin (1985), which is not based on the perfect gas assumption and which can be use under varying inlet conditions, where v_1 is the specific steam volume at the inlet:

$$\dot{m} = k\sqrt{\frac{P_1{}^2 - P_2{}^2}{P_1 v_1}} \tag{2}$$

In this paper, the derivation that will be used is based on a formula provided by Dixon and Hall (2014). The formula is an improved and more general version of Equation 2, considering the effect when operating outside the normal low loss region of the blade rows. This formula is the cone law of a multistage turbine, with P_{2d} the outlet pressure at design conditions:

$$\frac{\dot{m}}{m} = \left(\sqrt{\frac{1-\left(\frac{P_2}{P_1}\right)^2}{1-\left(\frac{P_{2d}}{P_1}\right)^2}} \right) \tag{3}$$

5. ASSESSMENT OF THE RESULTS AND DISCUSSION

5.1 Fluid chemistry and steam quality

Turbine scaling is one of the major problems encountered in geothermal utilization. There are several types of deposition that form on the turbine blades that can cause a problem in the electricity generation. Two common causes are deposition of solids carried over in the steam from the brine and formation of deposits by a chemical reaction between chemicals in the steam and turbine blade materials. The most common and easy to manage are the solids that are largely soluble in water and can thus be washed off with relative ease, whereas the other type of deposits adhere to the blades very tenaciously.

The chemical composition of the scales suggests that the major cause of the problem at M1GPP is the deposition of solids carried over in the steam. The purpose of this study is to assess data relative to the formation of such scaling on steam turbine blades, to identify the causes and look for a way of preventing it.

The data used are results of chemical analysis of samples from the different sampling points provided for this investigation. There are two sources of fluid entering the turbine: one is the supply steam and the other one is the fluid used for turbine blade washing.

The steam condensate chemistry is useful to determine the origin and nature of the scaling deposits accumulated in the turbine. Based on the XRD results, sodium chloride and calcite are the major compounds found on the turbine blades. Both are evaporation products and the constituents needed for their formation are present in the geothermal fluid. The solute concentrations in condensate can help to determine which parts of the system have high potential for deposition, and whether the online scrubbing and the drain pots/steam traps are collecting all impurities or carry-over from the steam before entering the turbine.

Separator liquid from the thermal ponds, ISK 2, ISK 3 and the fluid from the hot-well pit are the sampling points where the condensate chemistry is regularly determined. Figure 27 shows these locations, but the monitoring results are shown in Figures 16-19. Table 3 lists the solute mass ratio of the fluids sampled from the different locations. The similar Na/Cl ratio in samples from the thermal pond (brine) and ISK 2 and ISK 3 suggests that the source of those elements are brine carry-over, but the sharp increase at the hot-well pit is due to the addition of soda ash (Na_2CO_3) to the liquid. On the other hand, the Ca/Cl and SiO_2/Cl ratios suggest that the origin of these solutes is the same for all three sampling points (ISK 2, ISK 3 and hot-well pit). The lower Ca/Cl and SiO_2/Cl ratios in the separated brine may be due to precipitation from the brine before sampling. However, the concentrations of Ca, Na, SiO_2 and Cl generally decrease from ISK 2 to ISK 3 (see Figures 16-19). The 20,000-fold increase in the Fe/Cl ratio from the separated brine to the steam pipeline suggest that the source of iron in the latter stages may be traced to corrosion of the pipeline or other surface installations. The solute mass ratio results suggest that the wetness of the steam is due to brine droplets that are carried over with steam and might cause scaling. However, the samples from ISK 3 suggest that the concentrations are not high and should not lead to massive scaling.

FIGURE 27: Location of sampling points

TABLE 3: Solute mass ratio results

Location	Ca/Cl	Na/Cl	SiO_2/Cl	Fe/Cl
Separated brine (thermal pond A)	0.014	0.81	0.052	0.0000081
ISK 2 (before interface valve)	0.19	0.90	0.25	0.15
ISK 3 (before entering turbine)	0.40	1.10	0.45	0.45
Washing fluid (hot-well pit)	0.30	237	0.26	0.095

As stated above, the reason for the high concentration of sodium in the washing fluid is chemical dosing used for the cooling tower fluid. Because of the high Na concentrations, it is possible that the source of sodium chloride deposited on the turbine blades is the fluid used for turbine blade washing. To confirm these results, it is necessary to relate to the simulation of data for the off-design performance of turbines using Stodola's cone law.

5.2 Turbine performance at off-design conditions by Stodola's cone law

The off-design condition analysis of turbine performance is necessary to determine and to confirm whether blockage is forming in the steam path, which is referred to as choking. To determine the choking in the turbine blades, Stodola's cone law is used. A simulation based on the turbine performance was modelled using the Scilab software. The calculation is based on equation (3) describing the cone law of a multistage turbine. The data used in the simulation are from two periods representing scenarios with and without turbine blade washing. More specifically, these periods are right after the major overhaul of the turbine and implementation of the modifications in the system, and one year after the overhaul. To make sure that no other concerns or issues can disturb the performance of the turbine, the focus of the simulation is on the steam flow, chamber pressure and the outlet pressure.

Due to the great influence of the pressure ratio on the design parameters, the cone is restructured to an almost straight line. Figure 28 shows the plot of the two scenarios; red points are the data right after the major overhaul and without turbine blade washing, while blue points are the data one year after the major overhaul and with turbine blade washing operations every two to three days.

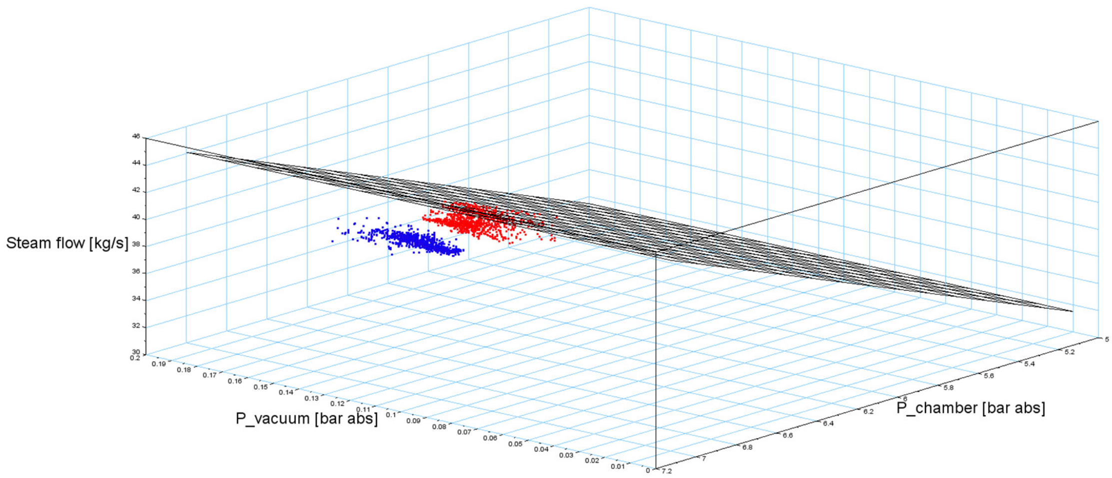

FIGURE 28: Plot of the two scenarios without washing (red) and with washing (blue), compared with Stodola's cone law

Based on the plot, the two points show that the turbine in off-design performance is still within the non-choked conditions as shown by the Stodola's cone law curve. So even though turbine blade washing is an effective way to clean deposits from the blades while the systems is online, both chemistry analysis and turbine performance suggest that the blade washing is one of the factors contributing to scale accumulation on the turbine parts.

5.2 Discussion

The scaling samples used for investigation in the chemistry analysis are collected after the two years of blade washing operations and are compared to the samples collected in the first major overhaul of the turbine. The turbine washing cleans the pre-existing scaling that is iron sulphide, however, a new type of scaling by sodium chloride is introduced. The washing fluid might be one of the main contributions to the accumulation of deposits on the turbine blades.

Part of the objective of this report is to look for possible mitigation that can be adapted for M1GPP operations to lessen or eliminate turbine blade washing. There are two possible mitigation approaches that can be used for the system, either acting on the steam supply or on the blade washing system. Currently, turbine blade washing is not yet terminated because of the operational history of M1GPP; it is still the only way to restore the gross load to its maximum value.

The first mitigation recommended for turbine washing is to change the fluid, using deionized water or non-aerated and non-treated condensate instead, in order to inject a lower total dissolved solid (TDS) fluid into the turbine. The condensate water used has a high content of oxygen and the oxygen can accelerate the corrosion and deposition processes on the turbine blades. Some plants in Indonesia are already using this method as a replacement for washing fluid (Adiprana and Yuniarto, 2010).

The mitigation suggestion for the steam supply is to compare scaling with and without washing, if applicable, to verify the real source of scaling. If the scaling is composed of iron-containing corrosion products, the source is the formation of iron sulphide or iron oxide from the piping or other surface installations. If the scaling is an evaporation product such as sodium chloride, the possible source is from the brine carry-over into turbine. Secondly, increasing the steam purity by installation of steam washing, installation of mist eliminator or demister, and improving the scrubbing system could help mitigate scaling. Based on the steam purity criteria provided by Fuji Electric, the recommended limit is 0.1 ppm and the maximum limit is 1 ppm. In Iceland, the recommend limit is usually applied for Fuji Electric turbines.

6. CONCLUSIONS

The results of scaling samples and the steam condensate chemical composition from the M1GPP is compared based on solute concentrations and the solute mass ratio. It was verified that the source of scaling is possibly the fluid used in the turbine blade washing.

The off-design performance of M1GPP is calculated based on Stodola's cone law to determine whether the parameters promote choking. A simulation of two different scenarios with and without washing was carried out using the Scilab software. The results suggest that both scenarios are under un-choked conditions as shown in Stodola's curve. The reason of increasing chamber pressure is the scaling present in the first stage of blades.

Both analyses suggest that the fluid used for turbine blade washing is the possible source of scaling. However, eliminating the turbine blade washing is not yet planned because based on the operational history of M1GPP, it helps to keep the gross load at its maximum value.

To mitigate the problems caused by scaling deposition in M1GPP steam turbine, the following actions should be considered:

- To change the washing fluid from cooling tower water with added soda ash to a fluid with lower total dissolve solids (TDS), for example deionized water or non-treated, non-oxygenated condensate;
- To compare the amount and composition of scaling with and without turbine blade washing, to verify the real source of scaling;
- To increase the steam purity by the installation of steam washing, installation of a mist eliminator or demister, or by improving the scrubbing system.

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To God be the glory!

REFERENCES

Adiprana, R., and Yuniarto, I.E., 2010: Gunung Salak geothermal power plant experience of scaling/ deposit: analysis, root cause and prevention. *Proceedings of the Word Geothermal Congress WGC2010, Bali, Indonesia,* 11 pp.

Buban, A., Villadolid-Abrigo, M., Sta. Maria, R., and Sussman, D., 1994: Geologic and reservoir model of the Maibarara geothermal field. *Proceedings of the 16th NZ Geothermal Workshop, Auckland, NZ*, 5-10.

Cooke, D.H., 1983: Modeling of off-design multistage turbine pressures by Stodola's ellipse. *Presented at Energy Inc. Pepse User's Group Meeting, Richmond, VI,* 205-234.

Craig, H., and Cox, H., 1970: Performance estimation of axial flow turbines. *Proceedings of the Institute of Mechanical Engineers, 185-1,* 407-424.

Dixon, S.L., and Hall, C.A., 2014: *Fluid mechanics and thermodynamics of turbomachinery* (7th ed.). Elsevier Inc., Oxford, 160-162.

Eustics, R., Erbes, M., and Phillips, J., 1987: *Analysis of the off-design performance and phased construction of integrated gasification combined cycle power plants. Vol. 1 and 2*. High Temperature Gasdynamics Lab., Electric Power Research Inst., Stanford Univ., Technical Report EPRI-AP-5027, Palo Alto, CA.

James, R., 1986: *Lectures on geothermal engineering*. UNU-GTP, Iceland, report 13, 50 pp.

Maturgo, K., and Fernandez, L.C., 2014: *Maibarara field resource assessment.* MGI, unpubl. internal report.

Maturgo, K., and Fernandez, L.C., 2019: *Maibarara field resource assessment.* MGI, unpubl. internal report.

Maturgo, K., Fernandez, L.C., Olivar, M.V., Esberto, M., Callos Jr., P., Isip, H., and Llenarizas, L., 2015: Challenges in the design and management of a 20-MWe geothermal field: The Maibarara geothermal field (Philippines) experience. *Proceedings of the World Geothermal Congress WGC2015, Melbourne, Australia*, 6 pp.

Murugan, R.S., and Subbarao, P., 2007: Off design performance prediction of steam turbines. *ASME 2007 International Mechanical Engineering Congress and Exposition, Seattle, WA*.

Olivar, M.V., Fernandez, L.C., Cruz, D.H., Isip, H.L., Tilos, R.E., and Del Rosatrio, E.P., 2011: Resource characterization, reserves estimation and development scheme of Maibarara geothermal field, Philippines. *Proceedings of the 9th Asian Geothermal Symposium, Kagoshima Prefecture, Japan,* 67-75.

Richardson, I., Addison, S., and Thompson, G., 2013: Steam purity considerations in geothermal power generation. *Proceedings of the 35th New Zealand Geothermal Workshop, Rotorua, NZ.*

Saunders, W.P., 2001: *Turbine steam path, maintenance and repair, Vol.1.* PennWell Corp., Tulsa, OK, 753 pp.

Silvestri, G., and Martin, H., 1985: *An update on partial arc admission turbine for cycling applications power generation division.* Westinghouse Electric Corporation, Orlando, FL.

Stodola, A., and Lowenstein, L., 1927: *Steam and gas turbines.* McGraw Hill Company, New York, NY, 316 pp.

Thórhallsson, S., 2012: Common problems faced in geothermal generation and how to deal with them. *Presented at Short Course on Geothermal Development and Geothermal Wells, organized by UNU-GTP and LaGeo, Santa Tecla, El Salvador,* 14 pp.

Van Der Mast, V., Goldman, E., and Soo-Hoo, R., 1986: Steam purity for geothermal power plants. *Geothermal Resources Council, Transactions, 10*, 353-358.