POIHIPI GEOTHERMAL POWER PLANT WATER COOLING SYSTEM – TAKING A HOLISTIC APPROACH TO INVESTIGATING PROBLEMS AND IMPLEMENTING SOLUTIONS

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ABSTRACT

The type of equipment comprising a geothermal power station main cooling water system can have a significant influence on the cooling water chemistry, sulphur deposition and micro- and macro-biological control in addition to the reservoir steam chemistry. A holistic approach is best when investigating problems to better understand the system and how best to implement solutions. Poihipi Road Power Station is the only geothermal steam turbine power station in New Zealand to have a shell-and-tube (surface) condenser, which has a significant influence on the cooling water chemistry compared to a direct-contact condenser. Prolific algae growth on the cooling tower also resulted in fouling throughout the cooling system and required frequent mechanical removal which increased the risk of dispersing into the air any Legionella bacteria that may have been present with the algae.

This paper provides an overview of the investigation approach performed to better understand the issues with the cooling water system and how best to address them.

1. INTRODUCTION

1.1 Poihipi Road Power Station

The Poihipi Road Power Station was originally built for the Geysers geothermal field in California with 55 MWe design capacity, but was never used until it was relocated to Poihipi Road in Taupo in 1996. Poihipi Road is the only geothermal steam power station in New Zealand to have a shell-and-tube (surface) condenser to date, this has a significant influence on the cooling water chemistry compared to a direct-contact condenser.

Initially Poihipi was supplied with dry steam from the margins of the Wairakei reservoir and the power station exported only around 25 MWe utilising four shallow dry steam wells (Zarrouk et al. 2006). In 2006 the steam supply was supplemented from the Te Mihi steamfield located within the greater Wairakei geothermal reservoir. It is now capable of 55 MWe output but mostly runs between 40 to 50 MWe to maximise the combined output with Wairakei and Te Mihi power stations (Harwood et al. 2015).

Poihipi Road is a single pressure power plant (operating around 3.5 to 4.3 barg) with steam entering a double flow turbine on a single shaft (Figure 1). The shell-and-tube condenser consists of an A and B side that splits the cooling water flow under both turbine ends. The condensed steam collects in the condenser hotwell and is pumped into the return line to the cooling tower, except for a smaller amount that is piped directly to the nearby Te Mihi Power Station for preferential use for steam scrubbing, brine acid dilution and occasionally turbine washing due to its low corrosion potential from a low dissolved oxygen concentration and high purity. Non-Condensable Gases (NCG) are removed from a combination of 4 × 25% capacity steam-jet ejectors and one Liquid Ring Vacuum Pump (LRVP) (there is also a duplicate standby set of ejectors and LRVP). The generator is hydrogen cooled. A simple plant schematic is shown in Figure 1.

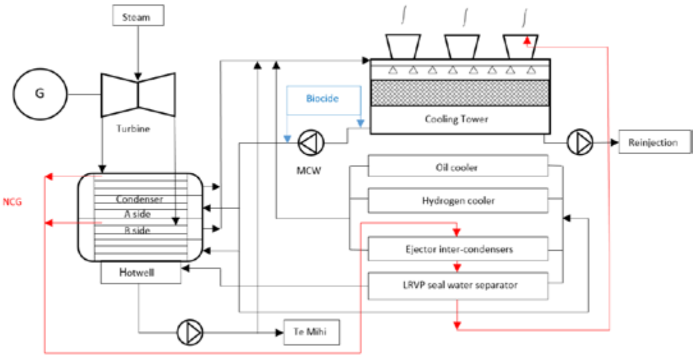


Figure 1: Schematic diagram of the Poihipi Road power station: Turbine, Condenser, Cooling water, Pumps and NCG extraction system.

The cooled recirculating main cooling water is pumped from the cooling tower basin by two 50% capacity Main Cooling Water (MCW) Pumps and mostly passes through the condenser tubes (double pass). A smaller auxiliary flow supplies seal water to the LRVPs (which then flows back to the condenser hotwell), and cooling water for the shell-and-tube: steam ejector (intercoolers) condensers, hydrogen and lubrication oil coolers. The warm water exiting the condenser tubes is mixed with surplus steam condensate from the condenser hotwell and auxiliary cooling water in the return line back to the cooling tower, where it is distributed over the flooded top deck portion of the cooling tower, to supply the individual spray nozzles to the splash-fill below.

The cooling tower is a cross-flow (forced draft) design with air entering through the sides of the cooling tower before being pulled upwards by the fans, Figure 2.

The wetted materials of construction in the cooling water circuit are made of 316 stainless steel condenser tubes, with 316L stainless steel tube sheets and 304L stainless steel shell (waterboxes), fiberglass piping and wooden internal cooling tower structure with wooden splash-fill. Auxiliary heat exchangers/LRVP are also made of stainless steel.

Figure 2: Poihipi cooling tower.

Routine cooling water chemical treatment was to dose every midnight a mixture of sodium hypochlorite and sodium bromide to form hypobromous acid as a biocide. This was dosed immediately downstream of the MCW pumps (Figure 1). The target concentration was between 1 to 2 mg/L (ppm) Free Residual “Chlorine” (FRC), which was intended to keep the condenser tubes clean.

1.2 Problems with cooling water system

The obvious problem with the cooling tower was the prolific algae growth on the top deck on the open water distribution boxes, Figure 3. This algae had to be removed every two to three months as water flow through the spray nozzles became restricted, and would overflow down the sides of the tower, reducing cooling efficiency. Thick deposits of algae were also prevalent on the sides of the cooling tower, but these were not routinely cleaned outside of major outages every 4 to 5 years, Figure 4.

Algae from the cooling tower was also released into the cooling water and would foul the MCW pump inlet screens and the downstream strainers of the cooling system, necessitating their regular cleaning.

Figure 3: Algae growth on open top deck water distribution boxes of cooling tower just prior to cleaning.

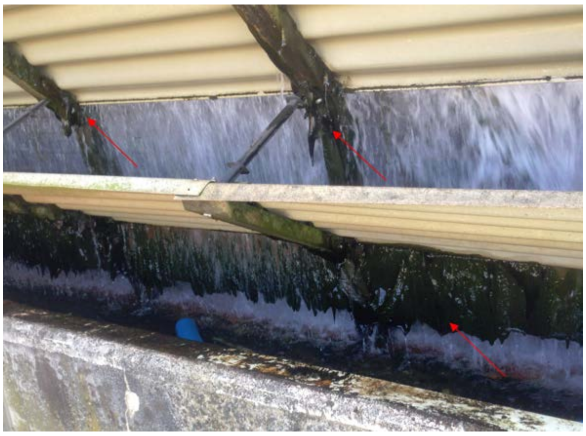


Figure 4: Algae growth on side of cooling tower.

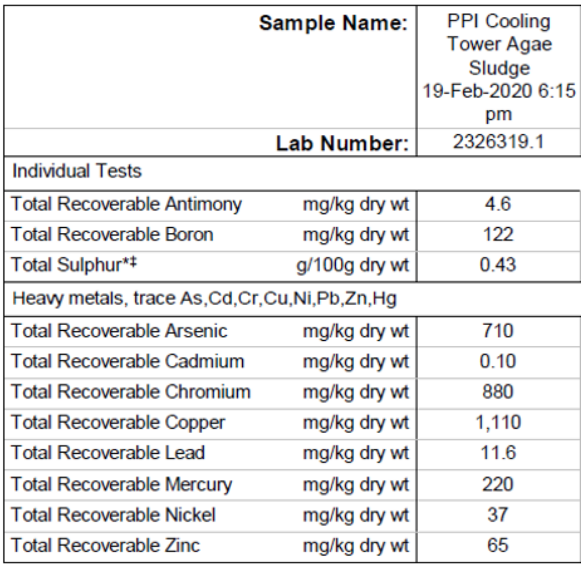
2. INVESTIGATION

A holistic approach was undertaken to: understand the cooling water macro- and micro-biological control issues and their consequences, review the effectiveness of the chemical treatment programme, consider the influence of the configuration of the main and auxiliary cooling water circuits may have on the cooling water chemistry, and determine the system volume, cycles of concentration and holding time index. This involved reviewing past records, discussions with operations and maintenance staff, inspection of cooling water equipment, tracer dye testing of the cooling water system, and water and deposits samples analysis.

2.1 Algae

A scraping of the algae was analysed microscopically which determined multiple algal species present and abundant fungal hyphae (Khor et al, 2019). A sample of the algae from the side of the cooling tower in Figure 4 was analysed for environmentally toxic elements for later disposal considerations when the tower could be thoroughly cleaned during the 2020 maintenance outage. The analysis results in Table 1 demonstrate the concentrating effect deposits can have on contaminants in the water (compare to Table 2).

Table 1: Analysis of algae for contaminants



	Sample Name:	PPI Cooling Tower Agae Sludge 19-Feb-2020 6:15 pm
	Lab Number:	2326319.1
Individual Tests		
Total Recoverable Antimony	mg/kg dry wt	4.6
Total Recoverable Boron	mg/kg dry wt	122
Total Sulphur*‡	g/100g dry wt	0.43
Heavy metals, trace As,Cd,Cr,Cu,Ni,Pb,Zn,Hg		
Total Recoverable Arsenic	mg/kg dry wt	710
Total Recoverable Cadmium	mg/kg dry wt	0.10
Total Recoverable Chromium	mg/kg dry wt	880
Total Recoverable Copper	mg/kg dry wt	1,110
Total Recoverable Lead	mg/kg dry wt	11.6
Total Recoverable Mercury	mg/kg dry wt	220
Total Recoverable Nickel	mg/kg dry wt	37
Total Recoverable Zinc	mg/kg dry wt	65

The original plywood deck covers over the water distribution boxes had been removed sometime in 2005 or 2006. Apparently this was done to check the water flow through the nozzles, and a number of the covers got damaged but were not replaced. This then exposed this area to full sunlight resulting in rapid algae growth.

The algae was mechanically removed from the top of the cooling tower using a vacuum cleaning system, driven by compressed air flowing through a pipe and out of a venturi air-ejector. Algae and water were sucked from the cleaner wand then separated in a sack filter, with the water leachate draining back into the cooling tower basin. Some water pumped out of the water distribution boxes was entrained in the air exiting the ejector creating a fine aerosol that was emitted at the top of the cooling tower near a stairway and at times close to the location of the workers doing the cleaning, Figure 5.

Figure 5: Aerosol emitted during algae removal.

This design feature was a potential safety risk as any Legionella bacteria in the algae could be present in the aerosol and inhaled by people nearby. Allowing the filter sack to drain back to the basin was also not good practice as the leachate could well have higher concentrations of Legionella that in the cooling water (Fallon, 2018). Legionella grows on surfaces within biofilm, disturbing the biofilm will release more Legionella into the cooling water if present.

Temporary improvements were made to the cleaning procedure in late 2018 to lower the Legionella transmission risk. A hose was connected over the air ejector to redirect the flow above the cooling tower basin so at least the aerosol had to pass through cascading water and the drift eliminators inside the tower before emitted to the outside air. Full face respirators with P3 filters were worn during cleaning operations.

The ultimate solution was to reinstate new plywood covers over the water distributions boxes. This would block out any sunlight to eliminate the growth of algae there and the need for frequent routine cleaning. This was scheduled to be done at the next major maintenance outage, originally in November 2019, but as the outage was deferred twice, was not completed until August 2020. During the outage, the sides of the cooling tower were also cleaned with moderate-pressure water washing, then the cooling system was drained and sludge deposits removed.

2.2 Cooling water treatment

The cooling water system had been operated without effective chemical treatment for many years. Despite being dosed daily, the biocide concentration was insufficient to control biofilm on the condenser tubes, or elsewhere. The actual biocide concentration in the cooling water had not been measured to confirm that the target concentration of 1 to 2 mg/L FRC at the condenser inlet was being achieved until years later in 2018. A mass balance calculation determined that even with no chlorine demand the maximum initial dose concentration would not exceed 0.05 mg/L FRC and at the completion of dosing 0.4 mg/L FRC. In practice, there was very high chlorine demand from algae and biofilm and <0.1 mg/L FRC could be achieved from direct FRC measurement using a common DPD (N, N-diethyl-p-phenylenediamine) reagent chlorine meter.

In July 2018 an initial trial dose of 40 mg/L hypochlorite (1,000 L of 15% sodium hypochlorite) was dosed into the cold well immediately upstream of the MCW pumps, Figure 1. This dose was not sufficient to overcome the high chlorine demand of the cooling water system in order to achieve a FRC reading. A further 40 mg/L hypochlorite was dosed 15 minutes later which resulted in >10 mg/L FRC for just over one hour, before rapidly dropping to 6, 2 then 0 mg/L FRC after a further 15, 35 and 50 minutes, respectively. The high concentration of hypochlorite that had to be dosed and the rapid decay in FRC indicates the very high chlorine demand from a heavily fouled cooling system.

2.3 Cooling water chemistry and microbial monitoring

The cooling tower basin water pH has generally remained above the target value of 6. The conductivity was typically between 30 to 60 μS/cm (3 to 6 mS/m). Conductivity and pH were measured weekly from grab (spot) samples, Figure 6. From October 2002 to June 2005, the pH typically remained above 6, with only a couple of excursions as low as pH 5. The pH dropped to 4.8 in October 2004 after the cooling tower basin was refilled with surface water from Lake Elliot – this water is more typical of that from a “duck pond” with high turbidity and organic loading than the normal high purity condensate. From September 2006 to August 2007 the pH was frequently below 6 and dropped as low as pH 4.1 – this period corresponded to when not all of the hotwell condensate was going to the cooling tower when there was problem with the blowdown reinjection well. The tower water began to cycle (concentrate) up, as shown by the higher conductivity measurements up to 350 μS/cm during this period, Figure 6. Since March 2008 to May 2016, the pH and conductivity of the basin water remained very stable generally between pH 6 to 7 and 30 to 60 μS/cm. From August 2016 to December 2019 the pH varied over a wider range between 5.9 and 8.9 while the conductivity did not generally change dramatically, Figure 6. From the records reviewed to date, the reasons for these low and high pH values are unknown.

The following microbial monitoring was performed: Legionella bacteria were monitored monthly in the cooling water since 2004, but only once detected above the detection limit of 10 colony forming units per milliliter (cfu/mL). Heterotrophic bacteria were monitored weekly using dipslides and were mostly below the target of $<10^5$ cfu/mL.

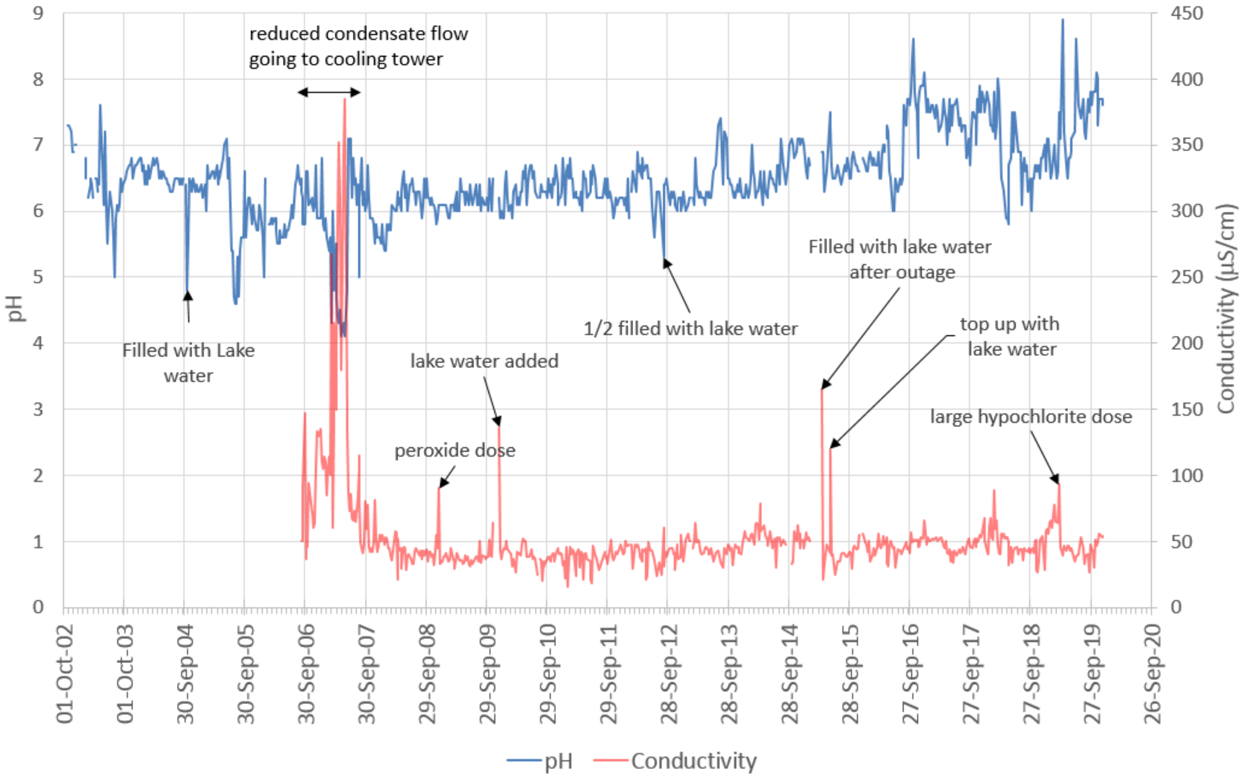


Figure 6: Weekly pH and conductivity measurements from grab samples of basin water

The slime mass accumulated on a coupon immersed in cooling water was scrapped off, dried and weighed fortnightly – this has since been discontinued as the trend results do not provide any useful or reliable information (Fallon, 2018).

Another performance criteria was to maintain minimal algae growth, but clearly this could not be achieved.

2.4 Condenser performance monitoring and inspection

The Terminal Temperature Difference (TTD) and condenser cleanliness factor were recorded during the weekly service visits as conformation that the condenser tubes were clean. The TTD is the exhaust steam temperature going into the condenser minus the condenser outlet water temperature. A TTD performance target of 2 to 2.5°C had been set to indicate that the condenser tubes were clean. The TTD did meet the performance target from 2002 until 2006 while the station only ran at half capacity, but then the TTD began to increase as the condenser vacuum worsened with increase in station load with the addition steam supply from Te Mihi. At near full station capacity the TTD was about double the performance target.

Economical design of a condenser will result in a TTD in the range of 2.8 to 5.6 °C (Guyer, 2013). The TTD performance target was achieved when the station was only running around 50% design capacity, and hence the condenser was oversized for this duty resulting in a low TTD because of this, rather than as an indication of clean condenser tubes.

The condenser cleanliness factor seemed remarkably high at around 90 to 100% most of the time between 2002 and 2015. There was a period in late May 2008 where a large volume of spent cooking oil was pumped into a newly drilled production well to try and remove a stuck drilling string, with oil observed on top of still water areas of the cooling tower water into early July. Another steam well was used from July. During the outage in September 2008 the condenser was inspected and observed to still have an oily film on the tubes on the steam side – the condenser was then cleaned with detergent to remove the oily residue. The condenser cleanliness dropped to 80 to 90% during the period of oil contamination which seems optimistic, and did not seem to have significantly improved after cleaning. The condenser instruction manual lists the tube design cleanliness as 70%. Design tube cleanliness can vary from 70 to 95% depending on tube water velocity, cooling water cleanliness and scaling potential. When the cooling water is clean or chlorinated, a cleanliness of 85% is normally used, with stainless steel tubes it is practical to use 90% (Guyer, 2013). While there would be no risk of scaling on the tubes due to the cooling water being supplied from steam condensate, stainless steels are susceptible to biofouling. The ineffectual routine biocide dosing would not have controlled biofilm on the condenser tubes, so the frequently high cleanliness values do not seem credible.

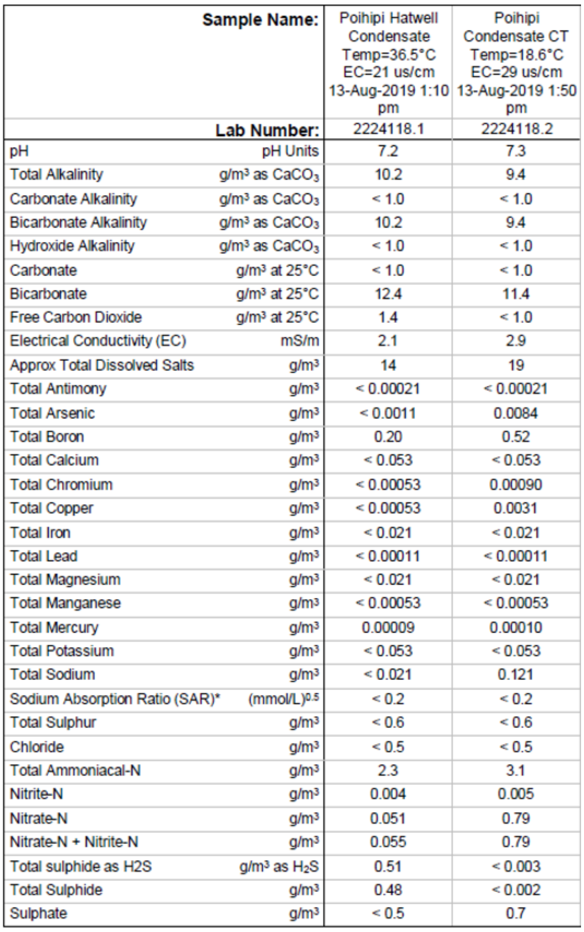
The manways on the B-side condenser inlet (Figure 1) and return waterboxes were opened during a short one-day maintenance outage on 10th July 2019. A thin, invisible, slippery biofilm could be felt on all internal surfaces but to a lesser extent inside the tubes. Swabs of the biofilm were sampled and bacteria analysed: Heterotrophic, iron-precipitating and *Pseudomonas* were detected. Heterotrophic microbial growth on surfaces appears to be the beginning stage in biofilm formation, which eventually become established biofilms. Production of exopolysaccharide "slime" by many of the microbes and the age and thickness of the biofilm can confer protection against many biocides. *Pseudomonas* species is a prolific slime-former, while iron-precipitating bacteria in these biofilms have enzymes that are capable of dissolving and utilising metallic iron (Khor et al, 2019).

Confirmation of the presence of established biofilm on the condenser tubes, supports the concern raised that the high condenser cleanliness values did not appear credible and that the biocide dosing was ineffective.

2.5 Analysis of condensate and cooling water

A comprehensive chemical analysis of a grab (spot) sample of the Poihipi condensate and of the cooling water were performed in August 2019, for the purpose of indicating how contaminated the water sources were. This was to provide information to help investigate potentially utilising more of the condensate for other more valuable purposes while also reducing future chemical dosing demand, by allowing the cooling water to cycle (concentrate) up further. The water analysis is also important when considering chemical treatment options for the cooling water. Note there was no chemical dosing occurring during or shortly before this water analysis that could have influenced these analysis results. The condensate sample was taken immediately downstream of the hotwell pumps and the cooling water sample from the condenser inlet, Table 2.

Table 2: Analysis of Poihipi condensate and cooling water.



	Sample Name:	Poihipi Hatwell Condensate Temp=36.5°C EC=21 us/cm 13-Aug-2019 1:10 pm	Poihipi Condensate CT Temp=18.6°C EC=29 us/cm 13-Aug-2019 1:50 pm
	Lab Number:	2224118.1	2224118.2
pH	pH Units	7.2	7.3
Total Alkalinity	g/m³ as $CaCO_3$	10.2	9.4
Carbonate Alkalinity	g/m³ as $CaCO_3$	< 1.0	< 1.0
Bicarbonate Alkalinity	g/m³ as $CaCO_3$	10.2	9.4
Hydroxide Alkalinity	g/m³ as $CaCO_3$	< 1.0	< 1.0
Carbonate	g/m³ at 25°C	< 1.0	< 1.0
Bicarbonate	g/m³ at 25°C	12.4	11.4
Free Carbon Dioxide	g/m³ at 25°C	1.4	< 1.0
Electrical Conductivity (EC)	mS/m	2.1	2.9
Approx Total Dissolved Salts	g/m³	14	19
Total Antimony	g/m³	< 0.00021	< 0.00021
Total Arsenic	g/m³	< 0.0011	0.0084
Total Boron	g/m³	0.20	0.52
Total Calcium	g/m³	< 0.053	< 0.053
Total Chromium	g/m³	< 0.00053	0.00090
Total Copper	g/m³	< 0.00053	0.0031
Total Iron	g/m³	< 0.021	< 0.021
Total Lead	g/m³	< 0.00011	< 0.00011
Total Magnesium	g/m³	< 0.021	< 0.021
Total Manganese	g/m³	< 0.00053	< 0.00053
Total Mercury	g/m³	0.00009	0.00010
Total Potassium	g/m³	< 0.053	< 0.053
Total Sodium	g/m³	< 0.021	0.121
Sodium Absorption Ratio (SAR)*	$(mmol/L)^{0.5}$	< 0.2	< 0.2
Total Sulphur	g/m³	< 0.6	< 0.6
Chloride	g/m³	< 0.5	< 0.5
Total Ammoniacal-N	g/m³	2.3	3.1
Nitrite-N	g/m³	0.004	0.005
Nitrate-N	g/m³	0.051	0.79
Nitrate-N + Nitrite-N	g/m³	0.055	0.79
Total sulphide as H2S	g/m³ as H_2S	0.51	< 0.003
Total Sulphide	g/m³	0.48	< 0.002
Sulphate	g/m³	< 0.5	0.7

In addition to the laboratory analysis, the specific conductivity was measured in situ from a continuous flowing sample, using a probe with a 0.1 cm^{-1} cell constant and with the high purity water temperature compensation setting. The measurements were 21 and 29 μS/cm (2.1 and 2.9 mS/m) for the condensate and cooling water samples, respectively, as corrected to a reference temperature of 25°C. The laboratory electrical conductivity results in Table 2 were exactly the same for the corresponding grab sample, while reassuring this was very unusual from field experience, particularly for such low conductivity water, which is why preference is given to measuring the conductivity in situ (similarly for pH measurements).

Main points to note from the analysis are: the conductivity and buffering capacity from ammonia (indicated by Total Ammoniacal-N) appear extremely low in both the condensate and cooling water for a geothermal power station. By comparison Te Mihi and Ohaaki power plant cooling water typically have a conductivity between 70 to 120 μS/cm and 340 to 600 μS/cm, respectively. Te Mihi condensate has twice the ammonia concentration than at Poihipi, yet this is still so low that Te Mihi requires continuous dosing of sodium hydroxide, to stabilise the pH of the cooling water due to acid produced from low numbers of Sulphur Oxidising Bacteria (SOB) (Young, 2018). Sulphate (SO_4^{2-}) is another interesting analysis as it can indicate the level of activity of SOB from its oxidation of H_2S to sulphuric acid (H_2SO_4) (Clark et al, 2017). There was only 0.7 g/m³ (ppm) sulphate in the cooling water at Poihipi compared to 10 to 35 g/m³ at Te Mihi (Young, 2018).

The total sulphide concentration (from H_2S) in the hotwell condensate at Poihipi is very similar to that at Te Mihi (Young, unpublished data). The sulphide does get practically all removed within the cooling tower, mostly to air but also as a food source for SOB. However, the actual total sulphide concentration in the return line to the Poihipi cooling tower is only approximately 3% of that at Te Mihi. This is due to most of the return line flow at Poihipi coming from the cooling water side of the surface condenser, unlike Te Mihi where all the return line flow is from the direct-contact condenser hotwell. There were also no sulphur deposits observed in the return line headers or spray nozzles on top of the Poihipi cooling tower as were seen at Te Mihi. Sulphur primarily forms by oxidation of the hydrogen sulphide firstly to thiosulphate then to sulphur by atmospheric oxygen dissolved in the open cooling water (Bacon et al, 1995).

The pH of the Poihipi cooling water was very stable above 6.0 despite no effective biocide dosing and very low natural buffering capacity from ammonia. The stable pH, very low sulphate present and lack of sulphur deposits on the return headers, all indicate that SOB are not present in any significant numbers due to a lack of food source. This can be solely attributed to the surface condenser, which sufficiently reduces the concentration of sulphide that reaches the cooling tower. Had a direct-contact condenser been instead installed then Poihipi would have experienced the same frequent low pH issues from SOB as encountered at Te Mihi (Young, 2018).

On the 15th October 2019, the dissolved oxygen was measured in situ from a continuous condensate sample flow to an Orbisphere Model 3650™ portable oxygen analyser which gave a measurement of 26 ppb (μg/L). The actual dissolved oxygen concentration may have been closer to 20 ppb as this particular analyser tends to have a slight (high) offset error when compared against calibrated on-line dissolved oxygen analysers permanently installed at Contact Energys' thermal power stations. (The same oxygen analyser measured 550 ppb on the hotwell condensate at Te Mihi power station with a direct-contact condenser 90 minutes earlier). The low dissolved oxygen concentration of the Poihipi condensate is because of the surface condenser, which along with the high purity, makes it a valuable low corrosion water source for Te Mihi power station and for potentially other uses.

The heavy metal analysis along with boron and nitrite/nitrate was included to see how contaminated the condensate and cooling water were as an indication to suitability for other potential uses for the liquid. The boron and nitrite/nitrate values in Table 2 are all below the maximum limits in the Drinking-water Standards for New Zealand 2005 (Revised 2018) and heavy metals concentrations were low (for comparison only, do not recommend using as a potable water source).

2.6 Seal water for LRVP

The chemistry conditions within the main cooling water can vary around the circuit, primarily between the hotwell and the cooling tower basin as dissolved hydrogen sulphide is almost entirely removed in the cooling tower. It is important to also consider chemistry differences in the auxiliary cooling water circuits compared to the main cooling water circuit, primarily the seal water circuit for the LRVP where the water is in direct contact with the NCG. The high concentration of hydrogen sulphide in the NCG will result in some oxidation to sulphur if the LRVP seal water contains dissolved oxygen. Typically the seal water is supplied from the open main cooling (tower) water, which will likely be saturated in dissolved oxygen (c. 8,000 ppb). In the case at Poihipi, Figure 7 shows sulphur deposits in a pipe spool piece and check valve on the moisture separator vessel drain to the condenser hotwell, downstream of the LRVP.

This sulphur deposition could be substantially reduced if seal water from the Poihipi condenser hotwell was used as it would be low in dissolved oxygen and not dosed with an oxidising biocide. However, the LRVP could lose approximately 50% efficiency due to the warmer hotwell condensate increasing the saturation pressure – a heat exchanger to first lower the condensate temperature would be required. An alternative seal water supply would also be required when starting up the power station when no condensate was available. Sulphur deposition is not a major problem and in the case of Poihipi, the drain line size will be increased in the 2020 outage.

Figure 7: Sulphur deposits on LRVP moisture separator drain line (above) and check valve.

2.7 Determining cooling system volume, holding time index and cycles of concentration.

There were no documented records that specified the actual water volume of the cooling water system, but it was thought to be around 3,500 m^3. A fluorimeter was used to accurately calculate the cooling water system volume, water loss rate from blowdown, drift, windage and leaks, and the Holding Time Index (HTI, or half-life). A volume of 5 L of inert fluorescent tracer dye was dosed into the cold well at 10:05 on 2nd May 2019 to achieve a target concentration of 1.5 mg/L. The fluorimeter had been cleaned and calibrated by the equipment provider the previous day to ensure measurement accuracy. The linear response range of this dye is between 0 and 3 mg/L, at higher concentrations the dose response becomes non-linear which will result in higher than actual system volume measurement. This dye had a product factor of 100, which meant that the fluorimeter read 100 times greater than the actual concentration, but the corrected values are reported here, Figure 8.

The fluorimeter measurements were recorded over several days to better observe the cooling tower basin level control, so to calculate the above parameters for normal operating conditions, Figure 8. The cooling tower basin level had been dropped lower than normal prior to the dye being dosed to avoid having blowdown on while the dye initially mixed evenly throughout the cooling water. The basin level control

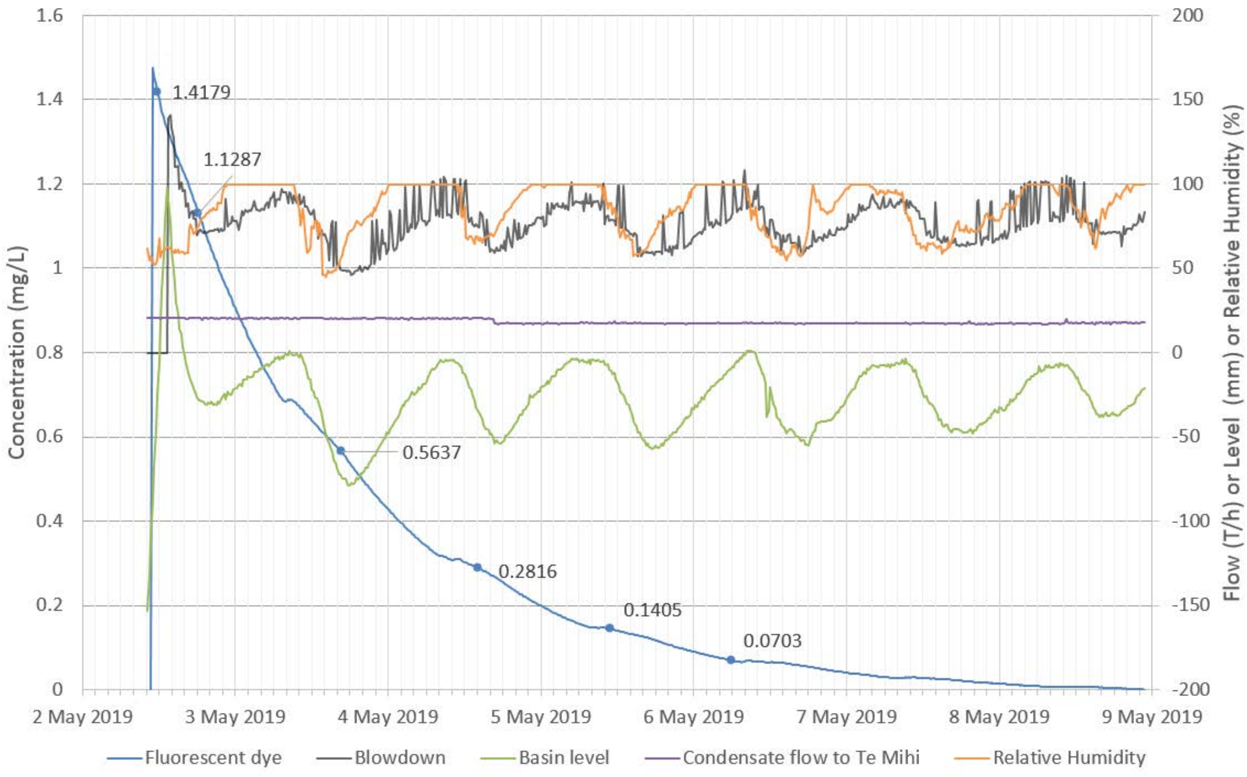


Figure 8: Fluorescent tracer dye test on Poihipi cooling water system.

normally controls between approximately 0 and -50 mm, but has a slow control response cycle that had a period of about 24 hours. Rather than taking the maximum peak concentration reading after the dye was added, instead recorded the concentration (1.4179 mg/L) once the basin level had returned to its average control level of -25 mm around 48 minutes later. This also allowed plenty of time for the dye to disperse evenly. The background fluorescent reading of the cooling water was -0.0203 mg/L before any dye was added, so the initial dye concentration at -25mm basin level was corrected to 1.4382 mg/L. The average system volume was 5,550 g dye ÷ 1.4382 mg/L (or g/m^3) = 3,860 m^3 at normal basin level. Similarly, the normal minimum (-50 mm) and maximum (0 mm) control range for the basin level corresponded to 3,810 and 3,900 m^3, respectively.

The total condensate flow minus the condensate flow to Te Mihi equals the makeup flow to the cooling water system. To determine the HTI, the dye concentration decline rate was analysed from 18:30 on 2nd May when continuous blowdown was operating and the basin level had returned close to its average control value. This gave a starting concentration of 1.1287 mg/L. The time the dye declined to half this concentration was at 16:45 on 3rd May with a value of 0.5637 mg/L, with the duration between these two concentration values being the holding time index of 22.5 hours. This process was repeated another three times until the dye concentration fell to 0.0703 mg/L as listed in Table 3 and plotted in Figure 8.

The holding time index and cycles of concentration can also be calculated from water mass balance:

$$\text{Makeup} = \text{Evaporation} + \text{Drift} + \text{Blowdown} \qquad (1)$$

$$\text{Holding time index (HTI)} = \frac{\underline{\text{system volume . ln 2}}}{(\text{blowdown} + \text{drift})} \qquad (2)$$

$$\text{Cycles of concentration} = \frac{\underline{\text{makeup}}}{(\text{blowdown} + \text{drift})} \qquad (3)$$

The effective blowdown = blowdown + drift + (leaks, if any). (4)

Other values in Table 3 were derived as follows:

Column 4 was calculated from the HTI determined from the dye concentration decay then rearranging equations (2) and (4) to give the Effective Blowdown (total liquid water loss not from evaporation).

Column 5 was the Average Blowdown flowrate over the period of the dye HTI, using the permanent flowmeter on the blowdown line.

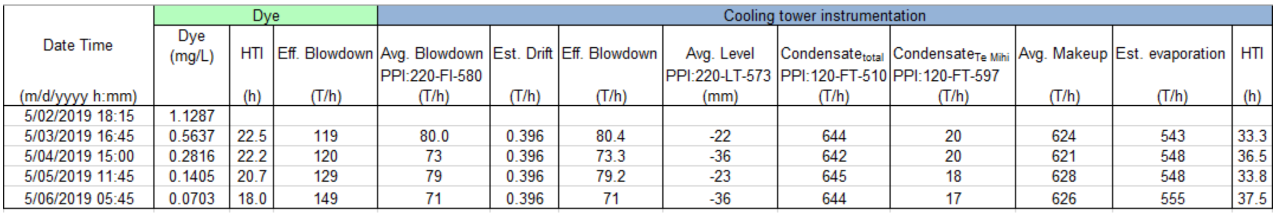
Column 6 was the Estimated Drift as stated on the Process Flow Diagram for the Poihipi cooling tower of 0.396 T/h.

Column 7 was the Effective Blowdown = column 5 + column 6.

Column 8 was the Average Level of the basin over the period of the dye HTI.

Column 9 was the Average Total Condensate flow from the condenser hotwell over the period of the dye HTI. A correction has been applied to the total condensate flowmeter values by subtracting the LRVP design seal water flowrate of 8.2 T/h from the total measured condensate flow, as the

Table 3: Data from fluorescent dye test compared with data from cooling tower flowmeters.



Date Time	Dye			Cooling tower instrumentation								
	Dye (mg/L)	HTI	Eff. Blowdown	Avg. Blowdown PPI:220-FI-580	Est. Drift	Eff. Blowdown	Avg. Level PPI:220-LT-573	Condensate$_{total}$ PPI:120-FT-510	Condensate$_{Te\ Mihi}$ PPI:120-FT-597	Avg. Makeup	Est. evaporation	HTI
(m/d/yyyy h:mm)		(h)	(T/h)	(T/h)	(T/h)	(T/h)	(mm)	(T/h)	(T/h)	(T/h)	(T/h)	(h)
5/02/2019 18:15	1.1287											
5/03/2019 16:45	0.5637	22.5	119	80.0	0.396	80.4	-22	644	20	624	543	33.3
5/04/2019 15:00	0.2816	22.2	120	73	0.396	73.3	-36	642	20	621	548	36.5
5/05/2019 11:45	0.1405	20.7	129	79	0.396	79.2	-23	645	18	628	548	33.8
5/06/2019 05:45	0.0703	18.0	149	71	0.396	71	-36	644	17	626	555	37.5

seal water is supplied from the cooling tower and discharges to the hotwell (Figure 1).

Column 10 was the Average Condensate flow to Te Mihi over the period of the dye HTI.

Column 11 was the Average Makeup flow to the cooling tower = column 9 – column 10.

Column 12 was the Estimated Evaporation by mass balance from rearranging equation (1), column 11 – column 7.

Column 13 was the HTI calculated from equations (2) and (4) using columns 7 and 11.

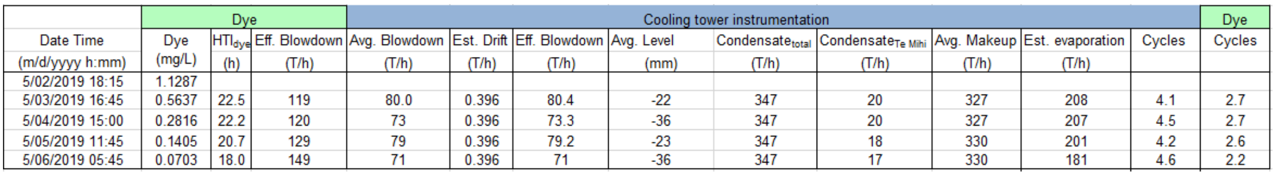
The HTI determined from the dye concentration decay averaged 20.9 hours which was longer than the 18.4 hours initially calculated by the equipment provider, but more accurately represented normal operational basin level and blowdown rates. The HTI was significantly lower than the average HTI of 35.3 hours derived from equation (2) using the installed blowdown flowmeter data and estimated drift, Table 3. The HTI derived from the dye concentration should be accurate given the recent calibration of the fluorimeter and reasonably accurately measuring the dosed dye volume. Therefore, this result points to a significant error in the blowdown flowrate measurement or a substantial water leak from the cooling water system. However, the difference between the dye effective blowdown and the instrumentation effective blowdown is not constant and ranged from 39 to 77 T/h during steady cooling tower operation between the HTI intervals in Table 3. If there was a water leak similar unaccounted water loss rates would be expected. Error in the drift estimation would be too small in magnitude to account for the differences in effective (total) blowdown between the dye and flowmeter derived data. Hence, it is suspected that the blowdown flowmeter was reading inaccurately.

The main steam flow into the demister before the turbine was steady at 355 T/h during the test periods in Table 3. Although not all of this steam enters the turbine, some is diverted for gas ejectors, etc. all the steam condensate practically ends up in the condenser hotwell. As the hotwell level was being controlled normally throughout the test period, the extracted hotwell condensate flow (minus the seal water flow) should equal the main steam flow, but 644 T/h ≠ 355 T/h (Table 3). By comparison, a Te Mihi unit rated at 83 MWe with a makeup condensate (steam flow) of 161 kg/s (580 T/h) and blowdown of 60 kg/s (216 T/h) = 2.7 cycles of concentration in the cooling tower. Also with a Te Mihi unit producing around 580 T/h condensate, a condensate flow of 652 T/h at Poihipi does not seem realistic – 355 T/h looks more comparable. The blowdown rates calculated directly from the dye concentration decay of around 130 T/h at Poihipi are also more in proportion with those from Te Mihi than the 80 T/h from the blowdown flowmeter, Table 3.

By substituting the main steam flow for the hotwell condensate flow and then subtracting the 8.2 T/h LRVP seal water flow, Table 3 can be recalculated as shown by Table 4. The average cycles of concentration derived from the fluorescent dye data was 2.6. The cycles of concentration calculated from the flowmeter instrumentation, equation (3), appears to be too high at over 4 cycles as it is using the spurious blowdown flowmeter data, Table 4. Cycles of concentration are usually easy to measure. A very soluble ion is chosen that is unlikely to form a solid deposit or be volatile and stripped into the air by the cooling tower. Cycles of concentration are simply the concentration of the ion in the cold well (or cooling tower basin) divided by the concentration in the makeup (hotwell condensate). Commonly used ions are chloride, potassium and sulphate – although sulphate or sulphide are not suitable for geothermal cooling towers due to the presence of $H_2S_{(aqueous)}$ (total sulphide) in the condensate being mostly stripped in the cooling tower and by SOB (which then produce sulphate as H_2SO_4).

The condensate and cooling water analysis in Table 2 has only boron that can be used to calculate cycles. The apparent boron cycles = 0.52/0.20 = 2.6 cycles, but the boron concentration in the condensate should be corrected for the 8.2 T/h LRVP seal water flow sourced from the cooling tower then discharged into the condenser hotwell. The total condensate flow was around 355 T/h. Therefore the corrected condensate boron concentration (from condensed steam only) is 0.1924 g/m^3, which gives boron cycles of 0.52/0.1924 = 2.7 cycles of concentration. This seems reasonable as geothermal cooling towers typically operate at

Table 4: Data from fluorescent dye test compared with data from cooling tower flowmeters (with main steam flow used instead of condensate flow).



	Dye			Cooling tower instrumentation									Dye
Date Time	Dye	HTI$_{dye}$	Eff. Blowdown	Avg. Blowdown	Est. Drift	Eff. Blowdown	Avg. Level	Condensate$_{total}$	Condensate$_{Te\ Mihi}$	Avg. Makeup	Est. evaporation	Cycles	Cycles
(m/d/yyyy h:mm)	(mg/L)	(h)	(T/h)	(T/h)	(T/h)	(T/h)	(mm)	(T/h)	(T/h)	(T/h)	(T/h)		
5/02/2019 18:15	1.1287												
5/03/2019 16:45	0.5637	22.5	119	80.0	0.396	80.4	-22	347	20	327	208	4.1	2.7
5/04/2019 15:00	0.2816	22.2	120	73	0.396	73.3	-36	347	20	327	207	4.5	2.7
5/05/2019 11:45	0.1405	20.7	129	79	0.396	79.2	-23	347	18	330	201	4.2	2.6
5/06/2019 05:45	0.0703	18.0	149	71	0.396	71	-36	347	17	330	181	4.6	2.2

around 3 cycles of concentration (Richardson et al, 2012), is similar to the Te Mihi cooling tower cycles and to the Poihipi cooling tower cycles of 2.6 derived from the fluorescent dye tests three months earlier.

2.8 Diverting condensate and cycling up the cooling water.

This was to provide information to help investigate potentially utilising more of the condensate for other more valuable purposes while also reducing future chemical dosing demand, by allowing the cooling water to cycle (concentrate) up further.

Presently 20 T/h (6%) of the condensate is diverted to the nearby Te Mihi power station, this increases the cooling tower cycles of concentration from 2.5 to 2.7, compared with if all the condensate went to the cooling tower, Table 5. The effect of additional condensate being diverted from the cooling tower on HTI and cycles is shown in Table 5. Based on this data, up to another 90 T/h of condensate could be diverted away from the cooling tower which would increase the HTI to approximately 90 hours and the cycles to approximately 8.

This number of cycles of concentration should not pose any scaling problems. Typically for non-geothermal cooling towers a high HTI (>48 hours) is undesirable as it can result in chemical treatment degradation – particularly for corrosion and scale inhibitors. While no corrosion or scale inhibitors are required for Poihipi, a high HTI may allow bacteria to accumulate to higher concentrations in the cooling water which would have to be carefully managed with well-timed biocide shock dosing. However, a higher HTI is potentially beneficial for dosing biocides as a lower average blowdown rate means the biocide would remain in the cooling water for longer. It is not recommended to cycle up the cooling tower in its present condition until after the cooling tower is mechanically cleaned and the cooling water system is thoroughly disinfected.

However, this analysis is for data obtained in May and needs to consider periods in summer where the evaporation rate will be higher, Figure 9. It appeared that once the maximum ambient temperature exceeds about 20 °C, along with the daytime drop in relative humidity, the evaporation increases enough that the basin level drops sufficiently to likely trigger a low level alarm at -100 mm, the operator then manually turns the blowdown control valve completely turned off for 3 to 5 hours to allow the basin level to recover until the basin level likely triggers a high level alarm at around 100 mm, then the blowdown control is switched back to automatic control - which then proceeds to aggressively lower the basin level. On the hottest days, the basin level will fall too low again and the blowdown valve must be manually turned off for a second time that day. (Adding a predictive evaporation factor to the blowdown control logic would improve stability in the basin level.)

The evaporation rate during the hottest days of the year can be estimated during the periods that the blowdown valve is off (as consider the blowdown flowmeter measurements to be inaccurate). Accumulation was calculated from the time it took for the basin level to increase from -50 mm (3,810 m^3) to 0 mm (3,900 m^3), Table 6 and Figure 9. A maximum evaporation rate of 265 T/h was calculated when the ambient temperature was between 27 and 30 °C with a relative humidity around 52%. This evaporation rate was used to

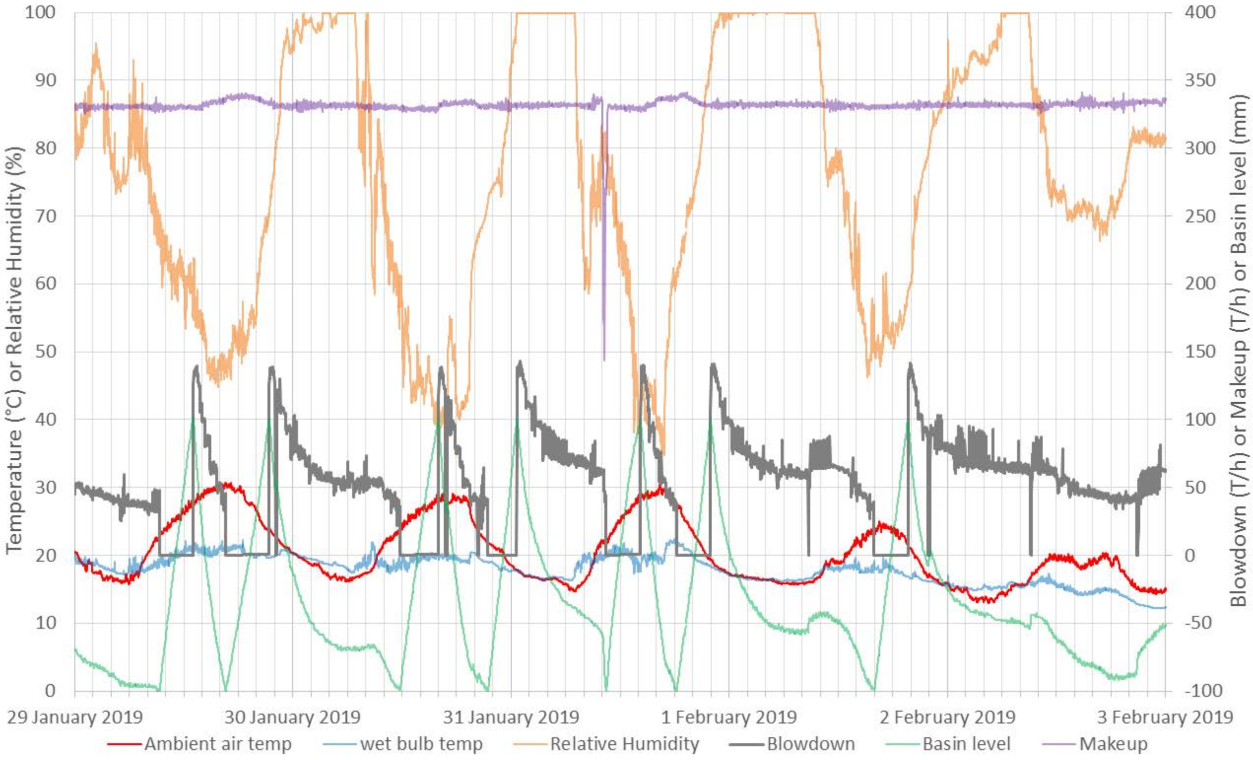
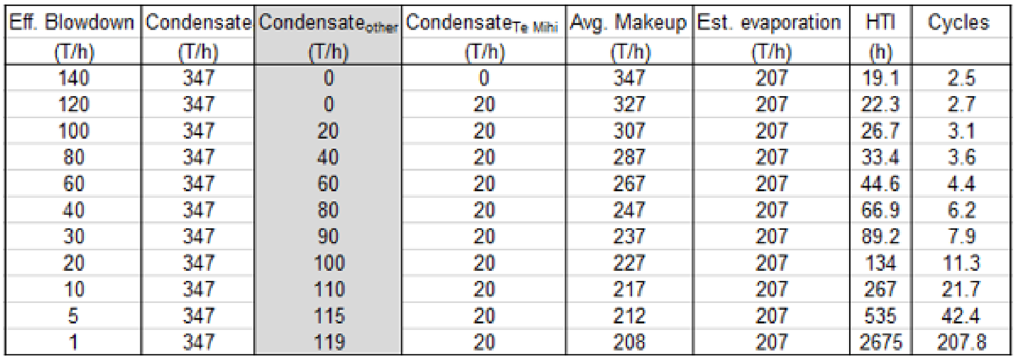


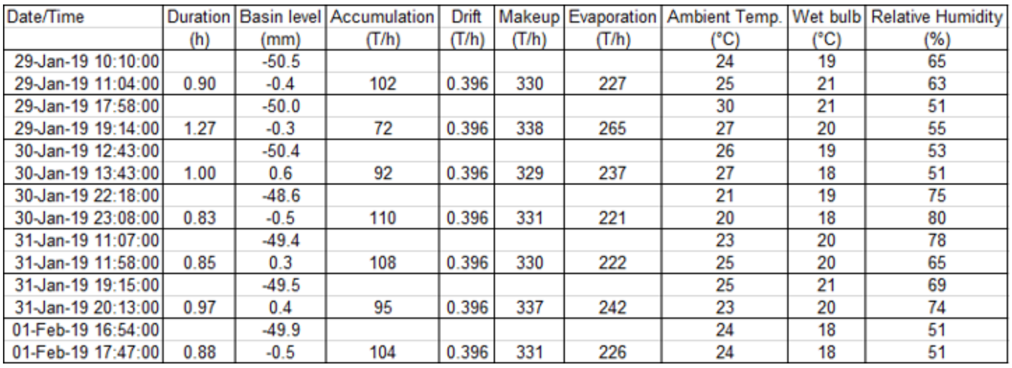
Figure 9: Poihipi cooling tower blowdown during hottest days in summer during 2019.

Table 5: Effect of diverting condensate from cooling tower (May).



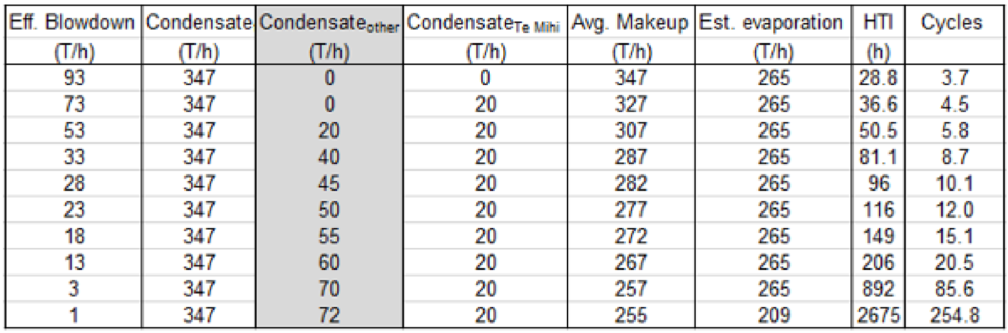
Eff. Blowdown (T/h)	Condensate (T/h)	Condensate$_{other}$ (T/h)	Condensate$_{Te\ Mihi}$ (T/h)	Avg. Makeup (T/h)	Est. evaporation (T/h)	HTI (h)	Cycles
140	347	0	0	347	207	19.1	2.5
120	347	0	20	327	207	22.3	2.7
100	347	20	20	307	207	26.7	3.1
80	347	40	20	287	207	33.4	3.6
60	347	60	20	267	207	44.6	4.4
40	347	80	20	247	207	66.9	6.2
30	347	90	20	237	207	89.2	7.9
20	347	100	20	227	207	134	11.3
10	347	110	20	217	207	267	21.7
5	347	115	20	212	207	535	42.4
1	347	119	20	208	207	2675	207.8

Table 6: Estimating evaporation during hottest days in summer 2019.



Date/Time	Duration (h)	Basin level (mm)	Accumulation (T/h)	Drift (T/h)	Makeup (T/h)	Evaporation (T/h)	Ambient Temp. (°C)	Wet bulb (°C)	Relative Humidity (%)
29-Jan-19 10:10:00		-50.5					24	19	65
29-Jan-19 11:04:00	0.90	-0.4	102	0.396	330	227	25	21	63
29-Jan-19 17:58:00		-50.0					30	21	51
29-Jan-19 19:14:00	1.27	-0.3	72	0.396	338	265	27	20	55
30-Jan-19 12:43:00		-50.4					26	19	53
30-Jan-19 13:43:00	1.00	0.6	92	0.396	329	237	27	18	51
30-Jan-19 22:18:00		-48.6					21	19	75
30-Jan-19 23:08:00	0.83	-0.5	110	0.396	331	221	20	18	80
31-Jan-19 11:07:00		-49.4					23	20	78
31-Jan-19 11:58:00	0.85	0.3	108	0.396	330	222	25	20	65
31-Jan-19 19:15:00		-49.5					25	21	69
31-Jan-19 20:13:00	0.97	0.4	95	0.396	337	242	23	20	74
01-Feb-19 16:54:00		-49.9					24	18	51
01-Feb-19 17:47:00	0.88	-0.5	104	0.396	331	226	24	18	51

Table 7: Effect of diverting condensate from cooling tower (peak summer).



Eff. Blowdown (T/h)	Condensate (T/h)	Condensate$_{other}$ (T/h)	Condensate$_{Te\ Mihi}$ (T/h)	Avg. Makeup (T/h)	Est. evaporation (T/h)	HTI (h)	Cycles
93	347	0	0	347	265	28.8	3.7
73	347	0	20	327	265	36.6	4.5
53	347	20	20	307	265	50.5	5.8
33	347	40	20	287	265	81.1	8.7
28	347	45	20	282	265	96	10.1
23	347	50	20	277	265	116	12.0
18	347	55	20	272	265	149	15.1
13	347	60	20	267	265	206	20.5
3	347	70	20	257	265	892	85.6
1	347	72	20	255	209	2675	254.8

recalculate Table 5 into Table 7. Diverting up to another 40 T/h of Poihipi condensate continuously appears to be feasible from this analysis, where the HTI and blowdown would be around 80 hours and 30 T/h, respectively. During cooler weather, possibly up to 90 T/h of condensate could be diverted elsewhere in addition to 20 T/h going to Te Mihi.

3. SUMMARY OF FINDINGS AND SOLUTIONS

There had been no effective routine biocide dosing of the Poihpi cooling water for many years. Despite this, the cooling water pH generally remained above 6 because the surface condenser significantly limited the concentration of sulphide (H_2S) entering the cooling tower and SOB could not become established. Removal of the water distriibution deck covers allowed prolific algae growth that required frequent mechanical cleaning.

Implementation of an effective biocide dosing programme was postponed until the cooling tower could be first be thoroughly mechanically cleaned and the deck covers reinstated. Aside from the high chlorine (or alternative biocide) demand requiring large and expensive dose quantities of chemicals, these would not be effective at fully penetrating and removing the heavy algae deposits or sludge. Also shock-dosing a heavily fouled cooling tower like Poihipi risked chunks of biofilm/algae being partially removed from the surface and clogging screens and strainers in the cooling water system, potentially resulting in tripping the station. Legionella bacteria may be present in the biofilm which are now released into the water, the chlorination must have sufficient concentration and contact time to kill these bacteria. Hence the need to start with a mechanically cleaned cooling tower first. It would also be unworkable to implement an effective biocide dosing programme without also preventing future prolific algae growth by first installing new deck covers to block sunlight to the heated return water to the cooling tower.

Hydrogen sulphide is readily oxidisable and reacts with sodium hypochlorite to form sulphur. Hence, oxidising biocides such as sodium hypochlorite are generally not used for geothermal cooling towers (Richardson et al. 2012). However, at Poihipi the main cooling water circuit is very low in sulphide (Table 2) and cheaper oxidising biocides may prove suitable as part of the chemical treatment programme. If oxidizing biocides are regularly dosed then as the LRVP seal water will be exposed to high H_2S concentrations in the NCG, should check that any increased sulphur deposition will not be problematic.

Clean condensate was also used to initially fill the cooling water system post cleaning instead of using the traditional heavily micro- and macro-biologically contaminated water source from Lake Elliot. This was achieved through a small temporary pipework modification to allow hotwell condensate at Te Mihi to be pumped to Poihipi in reverse via the existing pipeline between the stations, Figure 1.

Post outage, an extensive four-week period of biocide dosing was planned to thoroughly clean and remove biofilm from all the wetted surfaces in the cooling water system. The condenser efficiency will be closely monitored before, during and after this period. Thereafter, a performance-based biocide dosing programme is intended, ideally using the condenser efficiency as an on-line monitor for biofilm growth on the condenser tubes to help determine the biocide dosing frequency and an effective dose concentration. Performance monitoring would also include monitoring condenser vacuum pressure, visual observation of algae growth on the sides of the cooling tower along with regular testing for Heterotrophic and Legionella bacteria.

The historic recorded condenser cleanliness data was obtained during the scheduled weekly chemistry service visit. This is not the best time to take the readings as daytime ambient changes can have a large influence on the cooling tower performance. It is better to take the readings early morning before daybreak when cooling water conditions are more stable.

3. CONCLUSION

By taking a holistic approach to investigating the issues with Poihipi cooling water system, the following conclusions have been made:

There had been no effective routine biocide dosing of the Poihpi cooling water for many years. Despite this and the very low ammonia buffering, the pH of the cooling water had remained generally very stable above pH 6. This was solely because the surface condenser substatially limited the concenetration of sulphide (H_2S) returning to the cooling tower to the extent that SOB could not effectively colonise due to a lack of food source.

Prior to the outage, the algae cleaning method was modified to capture the aerosol from the air-ejector and redirect it inside the bottom of the cooling tower. This should reduce the risk of potentially spreading Legionella bacteria in the air in the interim.

The entire cooling tower must be throughly cleaned mechanically during the 2020 outage before any changes to an effective chemical tratment programe can be implemented. Deck covers must then be reinstalled to prevent prolific alage growth in the water distribution boxes. This would be followed by an extensive inital chemical clean to remove biofilm from the cooling water system.

Subsequent chemical treatment should move towards performanced-based dosing based on the condenser heat exchange efficency/vaccum pressure plus algal and microbiological control. Monitor sulphur deposition rates in LRVP seal water system if decide to regularly dose sodium hypochlorite.

Explore opportunities to utilise up to 40 T/h condensate elsewhere by diverting from the cooling tower makeup. Then trial with through monitoring.

Recalibrate/service condensate and cooling tower blowdown flowmeters.

The surface condenser at Poihipi has some advanatges over a direct-contact condenser: low oxygen and higher purity condensate uncontaminated by cooling water dosing chemicals that can be used for other applications, plus easier and cheaper cooling water chemical dosing is required.

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