GEOTHERMAL STEAM PURITY MODELLING – THEORY AND PRACTICE

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ABSTRACT

Geothermal steam purity modelling is considered by some to be an esoteric exercise. Two experienced practitioners in geothermal process engineering and geothermal chemistry seek to demystify steam purity modelling for the next generation of practitioners. This is done by explaining the basic principles used (along with key assumptions) and how modelling can assist steam separation and scrubbing pipeline design. Verified by drain-pot sampling, it provides an accurate measure of the overall efficiency of steam line scrubbing and gives confidence in the level of steam purity at the turbine - a key parameter operators are interested in.

Steam purity modelling considers initial steam separation performance and quantifies heat and mass transfer within steam lines in discrete stages, corresponding to each successive condensate removal point as well as final demisting prior to admission to the power plant. Chloride ion is a representative dissolved impurity that is non-volatile and remains entirely with the liquid phase in each stage; it is present in steam lines due to minor amounts of brine carry-over. The removal of slightly volatile silica can also be accounted for. Heat loss from pipelines can produce significant amounts of steam condensate which is involved in solution/mixing within each stage. If the condensation can be reasonably estimated in any section, then it can be used as a dilution-tracer to calculate the purity of the total steam flow in that section.

Assumptions about turbulent mixing of steam and brine/condensate and attainment of chemical equilibrium in each stage are explained, along with guidance on acceptable scrubbing velocity criteria, and the effectiveness of condensate removal at drop pots.

Insights that may be gained from steam purity modelling are discussed, and "proof" of the validity of modelling is provided by comparing modelling predictions with generalised (i.e. non-specific) geothermal steam system data.

1. INTRODUCTION

1.1 What is Steam Purity?

Steam purity is typically considered in terms of the level of dissolved solids such as chloride ion, silica, and iron. Levels of impurities are generally expected to be less than 0.1 ppm for individual species, and no more than 0.5 ppm total dissolved solids.

Steam purity should not be confused with steam quality which is a thermodynamic term for dryness (or it's complement, wetness). That said, steam purity and steam quality are inter-related because the impurities generally reside in the liquid phase that is present in slightly wet steam. One notable exception to this is silica, which has slight volatility in steam. (For example, at 190 °C the ratio of silica concentration in liquid to that in steam is approx. 4,000:1.)

Throughout this paper, we will focus on chloride ion as a non-volatile impurity, and silica as a volatile impurity. The reasons for this are that these components are reasonably abundant in geothermal fluids, are representative of non-volatile or volatile impurities, and they cause the greatest concern in terms of steam impurity impacts - scaling and corrosion. (Richardson et. al (2013) state that chloride is subject to volatile transport, but this needs to be considered relative to silica; at 25 bar the distribution coefficient for sodium chloride is 1×10^{-5} whereas silica at the same pressure is 3×10^{-4}; this thirty-fold difference in volatility means chloride is markedly less volatile than silica. And Figure 2 in the same paper indicates a twenty-fold difference in saturation pressure for the same distribution coefficient.)

Figure 1 is a simple schematic showing a two-phase steam separation system and a condensing power plant. Impurities in separated steam originate from small amounts of brine that "carry-over" with steam in the separator. These impurities are removed with liquid through condensate drain-pots (CDPs) and scrubber/demisters. Any impurities that reach the turbine may be seen in the turbine drains and the cooling water circuit.

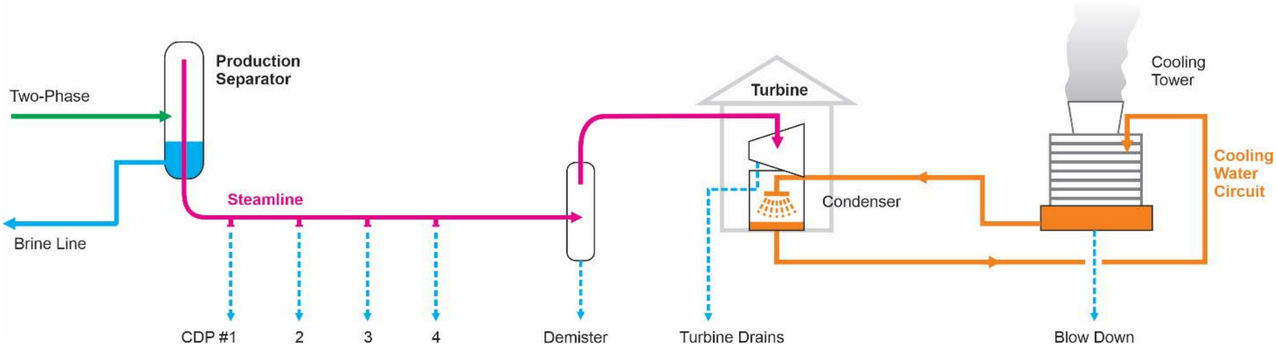

Figure 1: Schematic of a condensing power plant showing points where liquid impurities originating from carryover are removed from the system (dotted blue lines)

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1.2 Basic Theory

The word “basic” is used advisedly; the way we perceive phase and chemical interactions occurring is relatively simple, as follows.

Consider a section of steam line, between one condensate drop pot and the next. Steam and liquid phases flow in the pipe, ideally with liquid flowing as an annular film on the pipe wall. The flow will be slightly wet (superheat should be avoided since impurities in liquid droplets can become suspended solids if the steam dries out). Condensate will form on the pipe walls (due to heat loss through the walls and insulation) rather than forming within the bulk steam.

Some liquid may also be present as fine droplets entrained in the steam flow. Proper selection of the line velocity should (and will) result in entrained droplets contacting the pipe wall and adhering due to surface tension; if the velocity is excessive two things can occur; (i) pressure drop leads to drying-out and superheating of the steam, or (ii) fluid shear stress at the wall may lead to droplets of liquid being re-entrained in the bulk (steam) flow (Rizaldy, et. al., 2016). Pipeline bends may draw entrained droplets to the pipe walls.

Morris et. al. (2015) refer to entrainment of mist in the steam, and note that CDP design principles, having sufficient line length for larger line sizes, and selecting appropriate steam velocity may be lost art. Rizaldy, et. al. (2016) discuss mechanisms for re-entrainment of droplets from the liquid film into the bulk steam, and note that further investigation and validation is needed. However, the work of Dobbie (2002) provides what the authors consider is a sound basis for determining suitable steam line velocities for differing line sizes, and operating pressures. Dobbie’s “Entrainment Number” gives a quantitative basis to mitigate re-entrainment of the liquid film into the bulk steam flow.

The flow will be turbulent, as indicated by steam Reynolds numbers in the turbulent flow range. This means there will be full mixing of entrained droplets with the steam, and good contact between bulk steam flow and the the thin liquid film present on the pipe wall. These factors mean that chemical interactions can occur readily in the bulk steam and between the steam and the liquid film, driven by marked solubility differences between steam and liquid.

Steam flow at the start of the section, minus condensation, gives the steam flow at the end of the section.

The liquid will be a combination of carry-over brine from the separator and condensed steam, with the proportion of condensate increasing in successive pipe sections; the liquid mass balance is as follows: liquid at start, plus condensation, equals liquid flow at the end of the section. (There is no need to consider whether the condensed steam is present within the annular wall film or droplets in the bulk steam, for the reasons given above).

Volatile as well as non-volatile impurities are conserved within the section of pipe (between CDPs). Non-volatile dissolved solids are present only in the liquid phase and become diluted due to condensate formation. Volatile impurities on the other hand will partition between liquid and vapour phases, according to a distribution coefficient which is pressure (temperature) dependent (e.g. Ellis and Mahon, 1977, Section 8.1). Because of the turbulent flow and presumed good mixing of steam and liquid, it is reasonable to assume chemical equilibrium is attained (between steam and liquid for volatile species, and within the liquid phase non-volatile impurities will be well mixed). The validity of this assumption can be confirmed by measurements of the levels of impurities in the underflows from successive CDPs.

At first thought, given the effort that goes into insulating pipe and vessels, one might expect that condensation rates would be low, but two things need to be borne in mind. Firstly, the heat loss in the steam system (pipe, CDPs, and vessels) can be significant; estimates made for some projects indicate cumulative heat losses of the order of hundreds of kW(thermal) and (if steam lines are large and/or extensive) this could be up to several MW_{th}. As the latent heat of condensation for steam at typical geothermal pipeline pressures is about 2 MJ/kg, a heat loss rate of say 500 kW_{th} yields a condensation rate of 0.25 kg/s, or 0.9 t/h. Secondly, if the steam has a dryness of, say, 99.95% at the separator outlet, the liquid present in the pipe is only 0.05% of the steam flow. Assuming a steam flow of say 500 t/h, the liquid present in the line would be 0.25 t/h, so condensation rates of around 0.9 t/h predominate. This is the main reason why levels of impurities decrease rapidly at successive CDPs. If the carryover flow is very low, relative to condensation rates, then impurity levels will fall more rapidly; a positive indication that separation efficiency is good and the scrubbing system is not under stress.

There is one other matter that needs to be considered; this is the liquid separation (or removal) efficiency, and it applies for separator vessels, scrubber/demister vessels, and the condensate pots (CDPs). There are well-established industry guidelines (methods) for estimating separator liquid removal efficiency, achieving effective CDP designs (Lee, 1982), and performance offerings by vendors for scrubber/demister vessels are readily obtained.

The above are the key considerations that are applied to model steam purity in geothermal service. It is worth noting that we generally consider liquid-dominated steamfields, but for vapour-dominated fields the same considerations generally apply, with additional complications due to particulate impurities that may be present in superheated steam at the wellhead, including elevated boron levels.

2. REPRESENTATIVE CASE STUDY - PREDICTION

2.1 Key Inputs

For the purposes of this paper, we have conceived a “representative” case with which to develop a steam purity model. Table 1 summarises the key parameters for the case study.

Fluid Enthalpy	1325 kJ/kg
Mass Flow	500 kg/s
Steam Pressure	12.5 barA
Silica in total flow	650 ppm
Chloride in total flow	1,500 ppm
Separator outlet dryness	99.95%
Steam line length x dia	250 m x 1.05 m
Steam line insulation	50 mm
CDP and Scrubber spacings	50 m
CDP efficiency	50%
Scrubber efficiency	90%

Table 1: Key Parameters for Modelling

2.2 Derived Parameters

Table 2 gives the main derived parameters for steam purity modelling.

Flash Fraction	26.2%
Steam & Brine Flows	131 & 369 kg/s
Silica in brine	881 ppm
Chloride in brine	2,032 ppm
Carry-Over Brine	65.5 g/s (0.05% * 131 kg/s)
Carry-Over chloride	133 mg/s
Carry-Over silica	57.7 mg/s
Silica in steam flow (i.e. volatile silica)	29.1 mg/s (i.e. about half of the silica present in carry-over brine)
Total silica flow (in steam and carry-over brine)	86.8 mg/s
Cond. rate (per 50 m)	21 g/s (42 kW$_{th}$ heat loss)

Table 2: Derived Parameters for Modelling

2.3 Steam Line Mass Balances

The following mass balances are calculated for the first section of steam line, from separator outlet to the end of the section immediately prior to the first CDP (values are at the end of the section).

Steam flow = 130.975 – 0.021 = 130.954 kg/s

Liquid flow = 0.0655 + 0.021 = 0.0865 kg/s

Chloride in liquid = 0.0655 * 2,032 / 0.0865 = 1,539 ppm

Total silica in steam flow = 0.0000577 + 0.0000291 = 0.0000868 kg/s = X*(0.087 +130.95/3,958), where X is the silica concentration in liquid phase and 3,958 is the distribution coefficient for silica at 190 °C / 12.5 barA (Ellis & Mahon (1977)). Note that, in regard to silica distribution between liquid and steam, the term 130.95/3,958 is the steam flow converted to an equivalent liquid flow (which simplifies the calculation made by Richardson, et. al. (2013)). Solve to get X = 726 ppm. Thus silica in liquid is now 0.0000628 kg/s and silica in steam is 0.000024 kg/s (or 726/3,958 = 0.183 ppm). The silica concentration in the total steam line flow is 86.8 mg/s ÷ 131.04 kg/s = 0.66 ppm.

At each CDP, 50% of the liquid is assumed to be removed from the steam line, along with the attendant dissolved impurities (whether they are non-volatile or volatile, since they are in equilibrium between the liquid and steam phases at that point). The liquid removed is 50% * 0.0865 kg/s = 0.0433 kg/s. Chloride in that flow is 0.0433 * 1,539 = 66.6 mg/s, and silica removed with the liquid is 31.4 mg/s. (Note that this is about one third of the total silica present in the steam line at that point! And since the chloride is only present in the liquid phase, it follows that 50% of the chloride content is eliminated at the CDP.)

In the next section of steam line, the following mass balance would be calculated at the end of the section.

Steam flow = 130.95 – 0.021 = 130.93 kg/s

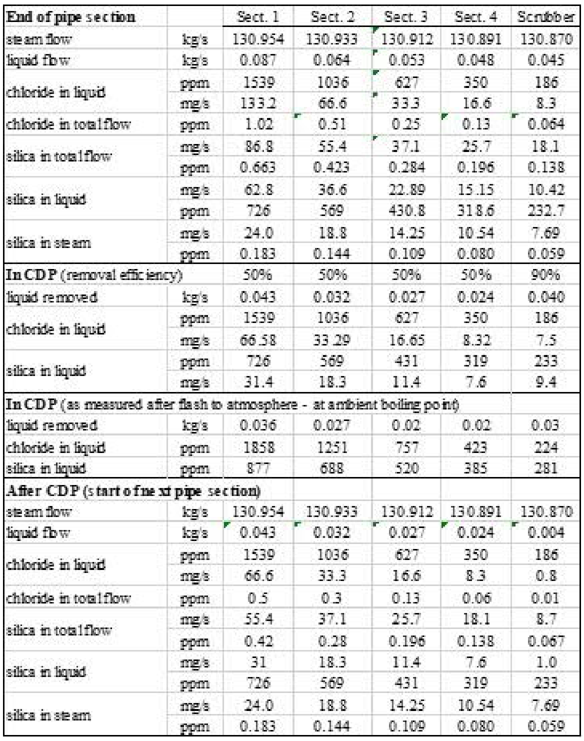
Liquid phase = 0.043 + 0.021 = 0.064 kg/s

Chloride in liquid = 0.043 * 1,539 / 0.064 = 1,036 ppm

Total silica in steam flow is now 86.8 mg/s less 31.4 mg/s removed in the previous CDP = 55.4 mg/s. The silica will re-equilibrate between the steam and liquid phases (the latter including the additional steam condensate) so that 0.0000554 kg/s = X' * (0.064 +130.93/3,958), where X' is the new silica concentration in liquid phase. Solve to get X' = 569 ppm. Thus silica in liquid is now 36.6 mg/s and silica in steam is 18.8 mg/s (or 0.144 ppm). The silica concentration in the total steam line flow is 55.4 mg/s ÷ 131.00 kg/s = 0.42 ppm.

The liquid removed at the second CDP is 50% * 0.064 kg/s = 0.032 kg/s. Chloride in that flow is 0.032 * 1,036 = 33.3 mg/s, and silica removed with the liquid is 0.032 * 569 = 18.3 mg/s.

Table 3 summarises the mass and impurity balances in each pipeline section, and includes a final scrubber vessel (instead of a CDP) with an assumed moisture removal efficiency of 90%.



End of pipe section		Sect. 1	Sect. 2	Sect. 3	Sect. 4	Scrubber
steam flow	kg/s	130.954	130.933	130.912	130.891	130.870
liquid flow	kg/s	0.087	0.064	0.053	0.048	0.045
chloride in liquid	ppm	1539	1036	627	350	186
	mg/s	133.2	66.6	33.3	16.6	8.3
chloride in total flow	ppm	1.02	0.51	0.25	0.13	0.064
silica in total flow	mg/s	86.8	55.4	37.1	25.7	18.1
	ppm	0.663	0.423	0.284	0.196	0.138
silica in liquid	mg/s	62.8	36.6	22.89	15.15	10.42
	ppm	726	569	430.8	318.6	232.7
silica in steam	mg/s	24.0	18.8	14.25	10.54	7.69
	ppm	0.183	0.144	0.109	0.080	0.059
In CDP (removal efficiency)		50%	50%	50%	50%	90%
liquid removed	kg/s	0.043	0.032	0.027	0.024	0.040
chloride in liquid	ppm	1539	1036	627	350	186
	mg/s	66.58	33.29	16.65	8.32	7.5
silica in liquid	ppm	726	569	431	319	233
	mg/s	31.4	18.3	11.4	7.6	9.4
In CDP (as measured after flash to atmosphere - at ambient boiling point)						
liquid removed	kg/s	0.036	0.027	0.02	0.02	0.03
chloride in liquid	ppm	1858	1251	757	423	224
silica in liquid	ppm	877	688	520	385	281
After CDP (start of next pipe section)						
steam flow	kg/s	130.954	130.933	130.912	130.891	130.870
liquid flow	kg/s	0.043	0.032	0.027	0.024	0.004
chloride in liquid	ppm	1539	1036	627	350	186
	mg/s	66.6	33.3	16.6	8.3	0.8
chloride in total flow	ppm	0.5	0.3	0.13	0.06	0.01
silica in total flow	mg/s	55.4	37.1	25.7	18.1	8.7
	ppm	0.42	0.28	0.196	0.138	0.067
silica in liquid	mg/s	31	18.3	11.4	7.6	1.0
	ppm	726	569	431	319	233
silica in steam	mg/s	24.0	18.8	14.25	10.54	7.69
	ppm	0.183	0.144	0.109	0.080	0.059

Table 3: Modelling Calculation Results

Figures 1 and 2 show the trend in (i) impurity levels and CDP liquid flows by CDP, and (ii) impurity levels in the total flow (steam plus small amounts of liquid) along the pipeline. (Values are at line conditions, as opposed to after flashing to atmosphere at ambient boiling point.)

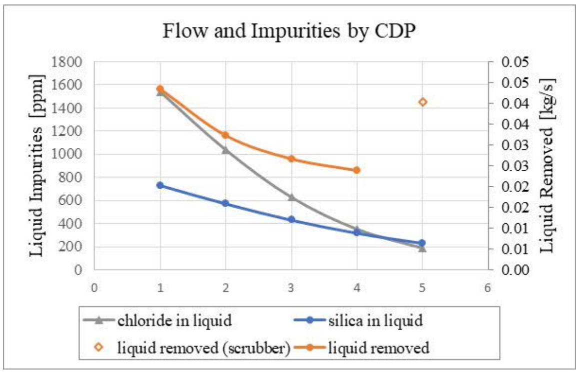


Figure 1: Modelled Flows and Impurities by Drain Point

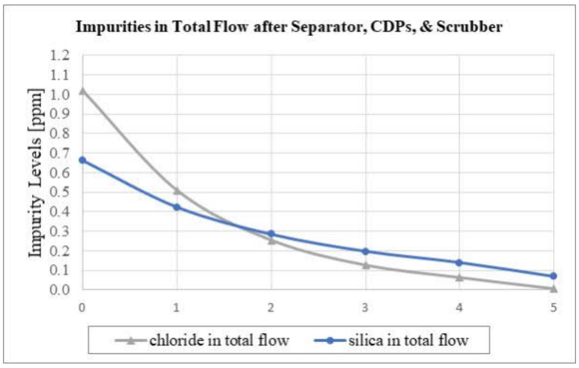


Figure 2: Modelled Impurities in Total Flow

2.4 Use of Spray Water for Steam Scrubbing

If spray water is used to provide steam scrubbing, this can easily be accommodated in the mass balance by including the wash water as additional condensate (and it should be injected a significant distance upstream of a CDP, so can be considered to enter the steam line immediately after an upstream CDP). An energy balance is necessary to account for extra condensation of steam due to the relatively cool wash water being heated to bulk steam temperature by condensing a small amount of steam. And any chloride and silica content of the wash water (which could be a few ppm) can also be considered in the overall mass balance.

Table 4 shows the effect of introducing cool (30°C) condensate (from the hotwell pump discharge) a short distance after CDP 2 (i.e. near the start of section 3) at a rate of 1% of the steam flow. The 1.31 kg/s of condensate generates an additional 0.45 kg/s of condensed steam after spraying into the steam flow, and the liquid flow at CDP 3 will be 0.032 + (1.31 + 0.451) + 0.021 = 1.814 kg/s.

End of pipe section		Sect. 1	Sect. 2	Sect. 3	Sect. 4	Scrubber
steam flow	kg/s	130.954	130.933	130.461	130.440	130.419
liquid flow	kg/s	0.087	0.064	1.814	0.928	0.485
chloride in liquid	ppm	1539	1036	21	20	19
	mg/s	133.2	66.6	37.2	18.6	9.3
chloride in total flow	ppm	1.02	0.51	0.28	0.14	0.071
silica in total flow	mg/s	86.8	55.4	37.5	19.1	9.9
	ppm	0.663	0.423	0.283	0.145	0.075
silica in liquid	mg/s	62.8	36.6	36.79	18.41	9.23
	ppm	726	569	20.3	19.8	19.0
silica in steam	mg/s	24.0	18.8	0.67	0.65	0.63
	ppm	0.183	0.144	0.005	0.005	0.005
In CDP (removal efficiency)		50%	50%	50%	50%	90%
liquid removed	kg/s	0.043	0.032	0.907	0.464	0.436
chloride in liquid	ppm	1539	1036	21	20	19
	mg/s	66.58	33.29	18.61	9.30	8.4
silica in liquid	ppm	726	569	20	20	19
	mg/s	31.4	18.3	18.4	9.2	8.3
In CDP (as measured after flash to atmosphere - at ambient boiling point)						
liquid removed	kg/s	0.036	0.027	0.75	0.38	0.36
chloride in liquid	ppm	1858	1251	25	24	23
silica in liquid	ppm	877	688	24	24	23
After CDP (start of next pipe section)						
steam flow	kg/s	130.954	130.933	130.461	130.440	130.419
liquid flow	kg/s	0.043	0.032	0.907	0.464	0.048
chloride in liquid	ppm	1539	1036	21	20	19
	mg/s	66.6	33.3	18.6	9.3	0.9
chloride in total flow	ppm	0.5	0.3	0.14	0.07	0.01
silica in total flow	mg/s	55.4	37.1	19.1	9.9	1.6
	ppm	0.42	0.28	0.145	0.075	0.012
silica in liquid	mg/s	31	18.3	18.4	9.2	0.9
	ppm	726	569	20	20	19
silica in steam	mg/s	24.0	18.8	0.67	0.65	0.63
	ppm	0.183	0.144	0.005	0.005	0.005

Table 4: Modelling Results with Wash Water

The corresponding graphs of flow and impurities in the CDP and scrubber drains, and impurities in the total steam flow are shown in Figures 3 and 4 for the case of wash spray applied after CDP 2.

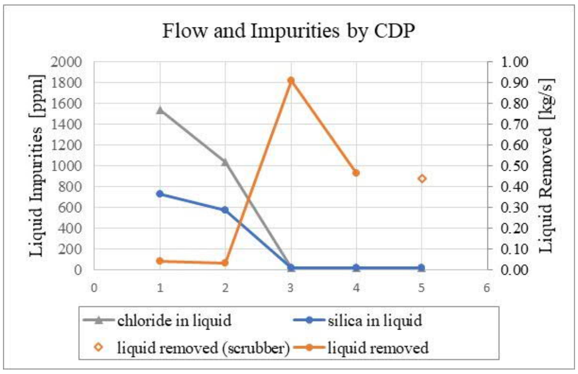


Figure 3: Modelled Flows and Impurities with Spray Wash Water

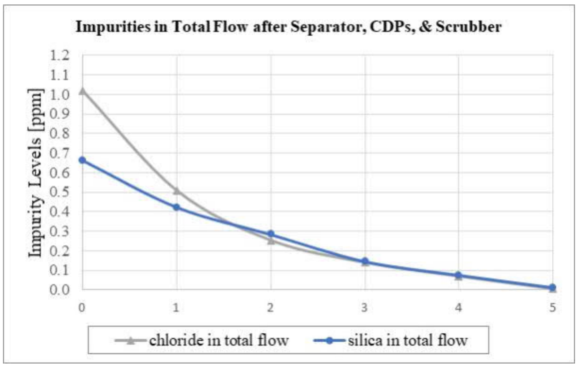


Figure 4: Modelled Impurities in Total Flow with Spray Wash Water

2.5 Measurable Low Flow Rates and Low Concentrations

It should be very clear from the above modelling that the flow of liquid in the steam line and out of each CDP can be very small, and the impurities (silica and chloride) may be at low concentrations. Importantly though, both the flow rates and the concentrations are readily measurable. For example, a CDP drain flow of, say, 0.032 kg/s (CDP 2) amounts to about 1.9 kg in one minute, or 9.6 kg in 5 minutes. Collected from the CDP, and adjusted for flash and density of the liquid at local boiling point, the liquid volume would be about 8.34 litre (7.98 kg) in 5 minutes.

Solute levels will obviously rise when the liquid is flashed to atmosphere, with CDP 2 chloride rising from 1,036 ppm (by weight) to 1,251 ppm in the collected liquid. However, the chloride flux leaving the line at the CDP is unaffected by flashing, since 1,251 ppm * 7.98 kg / 300s = 33.3 mg/s. So in field testing it is not necessary to correct for flash.

Chloride and silica levels in liquid can be measured down to very low levels, so 1,251 ppm chloride and 688 ppm silica are readily measurable.

2.6 Inferences from Measured Data

Based on the above observations, modelling assumptions and predictions can be validated by field measurements. This includes separator efficiency (i.e. the amount of carry-over brine), individual CDP efficiencies, and scrubber efficiency. Chloride (or sodium) ion is a very reliable tracer for these assessments, but injected tracers (either proprietary ones of commercially available chemicals) can also be used to determine liquid (and steam) flow rates.

Both the flow rate and concentration of chloride are measured for successive CDP drains and the scrubber underflow; silica can also be measured to compare with modelled values. Flow and chloride concentration in the steam leaving the scrubber is also measured, for example by isokinetic probe sampling. If the aggregate chloride flux (the product of flow rate and concentration) is calculated for all CDP drains, the scrubber drain, and the steam going to the power plant, then dividing this flux by the chloride ion concentration in the separated brine gives the carry-over brine flow; i.e. ($m_{carry-over}$) is given by:

$$\frac{\sum_{CDPs} flow.[Cl^-] + scr\,flow.[Cl^-] + stm\,flow.[Cl^-]}{[Cl^-]_{sep\,brine}}$$

Once the carry-over brine flow is known, the amount of condensate formed in each section of the steam line can be estimated; this is based on the change in chloride ion concentration from one drain point to the next. For example, for Section 3 of the steam line, the chloride level drops from 1036 ppm to 627 ppm; this is because the liquid flow of 0.032 kg/s after the CDP increases by 0.021 kg/s of condensate to 0.053 kg/s. (The amount of condensate formed can be used to validate the heat loss estimates made during modelling.)

Deducting the liquid flow extracted at each CDP allows the liquid at the start of the next pipe section to be estimated and, again, the degree of dilution of chloride ion in the next section informs the amount of condensation there.

Comparing the drain flow from each CDP to the estimated liquid flow in the line at the CDP allows the CDP liquid removal efficiency to be calculated. (A proviso on this is that the section length should be reasonably long so that most of the condensate formed in the section has fallen to the invert of the pipe and can be captured by the CDP. If this is not the case, the CDP collection efficiency would be under-estimated.)

2.7 Design for Steam Purity Testing

To conduct the above testing rigorously it is essential that there is good access for sampling and flow measurement. This should be considered in the engineering design.

It is important that each CDP is configured so that samples can be collected for analysis, and the flow rate can be measured safely. If, for example, a CDP was flooded, it may be preferable to measure flow rates and collect samples at subsequent CDPs.

It is also very useful if the CDP and scrubber drains all discharge to a thermal pond for disposal, as opposed to feeding directly or indirectly into the cooling water circuit. The reason for this is that the cooling circuit steady state chloride level can be used to estimate the chloride level in the steam leaving the scrubber and entering the power plant. Provided there are no other sources of the chosen tracer, by adjusting for the cycles of concentration in the cooling circuit, the incoming steam chloride concentration can be derived. For example, if 75% of the steam condensate is evaporated in the cooling tower (and 25% is blown down), then the chloride content of the incoming steam will be concentrated four-fold; a cooling circuit chloride level of say 0.2 ppm would point to a steam chloride content of 0.05 ppm, which should align with isokinetic samples taken at the scrubber outlet. This assumes there is no significant liquid phase on the pipe walls at the scrubber outlet, since isokinetic sampling would likely miss such liquid; by the time the steam reaches the scrubber outlet, any liquid phase present in the line will be practically all condensed steam, with negligible chloride ion content. It also assumes that turbine drains discharge to the condenser (and thence to the cooling circuit) so all incoming chloride ion is captured.

3. REPRESENTATIVE CASE STUDY - FIELD DATA

3.1 Plant A

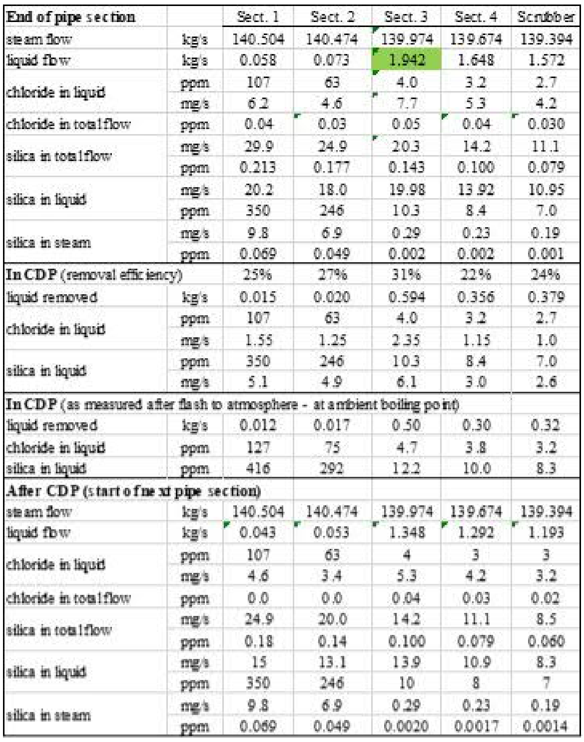
Steam purity testing was undertaken at commissioning of this plant, and the field results are shown in Table 5.

Drain ID	**Flow Rate (kg/s)**	**[Cl-]* (ppm)**	**Comment**
CDP 1	0.012	127	
CDP 2	0.017	75	
	1.40	wash water injection	
CDP 3	0.5	4	
CDP 4	0.3	3.3	
CDPs 3+4	0.8	3.4	combined
Scrubber	0.56	3.2	
Steam	140	0.01	

* as flashed to atmosphere (but flows are metered at line pressure)

Table 5: Field Results (with Wash Water)

Modelling of the field data was undertaken, with the rates of condensation due to heat loss estimated from the changes in chloride ion levels. The results are shown in Table 6.



End of pipe section		Sect. 1	Sect. 2	Sect. 3	Sect. 4	Scrubber
steam flow	kg/s	140.504	140.474	139.974	139.674	139.394
liquid flow	kg/s	0.058	0.073	1.942	1.648	1.572
chloride in liquid	ppm	107	63	4.0	3.2	2.7
	mg/s	6.2	4.6	7.7	5.3	4.2
chloride in total flow	ppm	0.04	0.03	0.05	0.04	0.030
silica in total flow	mg/s	29.9	24.9	20.3	14.2	11.1
	ppm	0.213	0.177	0.143	0.100	0.079
silica in liquid	mg/s	20.2	18.0	19.98	13.92	10.95
	ppm	350	246	10.3	8.4	7.0
silica in steam	mg/s	9.8	6.9	0.29	0.23	0.19
	ppm	0.069	0.049	0.002	0.002	0.001
In CDP (removal efficiency)		25%	27%	31%	22%	24%
liquid removed	kg/s	0.015	0.020	0.594	0.356	0.379
chloride in liquid	ppm	107	63	4.0	3.2	2.7
	mg/s	1.55	1.25	2.35	1.15	1.0
silica in liquid	ppm	350	246	10.3	8.4	7.0
	mg/s	5.1	4.9	6.1	3.0	2.6
In CDP (as measured after flash to atmosphere - at ambient boiling point)						
liquid removed	kg/s	0.012	0.017	0.50	0.30	0.32
chloride in liquid	ppm	127	75	4.7	3.8	3.2
silica in liquid	ppm	416	292	12.2	10.0	8.3
After CDP (start of next pipe section)						
steam flow	kg/s	140.504	140.474	139.974	139.674	139.394
liquid flow	kg/s	0.043	0.053	1.348	1.292	1.193
chloride in liquid	ppm	107	63	4	3	3
	mg/s	4.6	3.4	5.3	4.2	3.2
chloride in total flow	ppm	0.0	0.0	0.04	0.03	0.02
silica in total flow	mg/s	24.9	20.0	14.2	11.1	8.5
	ppm	0.18	0.14	0.100	0.079	0.060
silica in liquid	mg/s	15	13.1	13.9	10.9	8.3
	ppm	350	246	10	8	7
silica in steam	mg/s	9.8	6.9	0.29	0.23	0.19
	ppm	0.069	0.049	0.0020	0.0017	0.0014

Table 6: Modelling Results with Wash Water

Modelling was able to match the CDP chloride levels reasonably well, especially for the first two CDPs (prior to introduction of wash water). Silica levels were also measured but actual values were much lower than modelled values, for all CDPs. The reason for this is uncertain, although it is thought the silica analyses may be in error. (The reason for this is that lower than expected silica values for CDP drains would imply that silica would be carried through the scrubber, but isokinetic samples indicated silica in the steam after the scrubber was between 0.015 and 0.03 ppm.)

3.2 Plant B

Steam purity testing was undertaken at commissioning of this plant, and the field results are shown in Table 7.

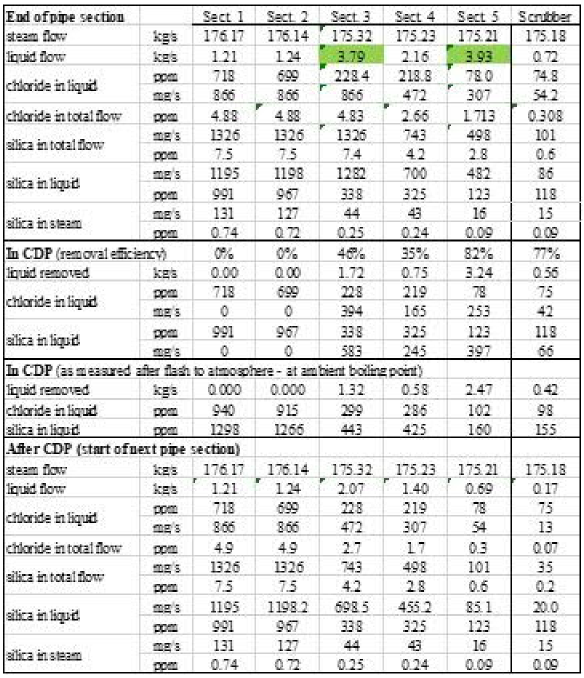
Drain ID	Flow Rate (kg/s)	[Cl-]* (ppm)	[SiO₂]* (ppm)	Comment
CDP 1	nil	940	1247	flooded
CDP 2	nil	915	1096	flooded
	1.74	wash water injection		
CDP 3	1.73	555	760	
CDP 4	0.76	55	95	
	1.74	wash water injection		
CDP 5	3.24	41	65	est. values
CDPs 3-5	5.72	195	275	aggregate
Scrubber	0.56	20	95	
Steam	175.2	<0.04	0.11	

* as flashed to atmosphere (but flows are metered at line pressure)

Table 7: Field Results (with Wash Water)

The measured chloride and silica levels in the cooling water circuit were less than 0.1 and approx. 0.26 ppm, corresponding to <0.025 ppm and 0.06 ppm respectively in the steam (based on four cycles of concentration).

Modelling of the field data was undertaken, with the rates of condensation due to heat loss estimated the changes in chloride ion levels. The results are shown in Table 8.



End of pipe section		Sect. 1	Sect. 2	Sect. 3	Sect. 4	Sect. 5	Scrubber
steam flow	kg/s	176.17	176.14	175.32	175.23	175.21	175.18
liquid flow	kg/s	1.21	1.24	3.79	2.16	3.93	0.72
chloride in liquid	ppm	718	699	228.4	218.8	78.0	74.8
	mg/s	866	866	866	472	307	54.2
chloride in total flow	ppm	4.88	4.88	4.83	2.66	1.713	0.308
silica in total flow	mg/s	1326	1326	1326	743	498	101
	ppm	7.5	7.5	7.4	4.2	2.8	0.6
silica in liquid	mg/s	1195	1198	1282	700	482	86
	ppm	991	967	338	325	123	118
silica in steam	mg/s	131	127	44	43	16	15
	ppm	0.74	0.72	0.25	0.24	0.09	0.09
In CDP (removal efficiency)		0%	0%	46%	35%	82%	77%
liquid removed	kg/s	0.00	0.00	1.72	0.75	3.24	0.56
chloride in liquid	ppm	718	699	228	219	78	75
	mg/s	0	0	394	165	253	42
silica in liquid	ppm	991	967	338	325	123	118
	mg/s	0	0	583	245	397	66
In CDP (as measured after flash to atmosphere - at ambient boiling point)							
liquid removed	kg/s	0.000	0.000	1.32	0.58	2.47	0.42
chloride in liquid	ppm	940	915	299	286	102	98
silica in liquid	ppm	1298	1266	443	425	160	155
After CDP (start of next pipe section)							
steam flow	kg/s	176.17	176.14	175.32	175.23	175.21	175.18
liquid flow	kg/s	1.21	1.24	2.07	1.40	0.69	0.17
chloride in liquid	ppm	718	699	228	219	78	75
	mg/s	866	866	472	307	54	13
chloride in total flow	ppm	4.9	4.9	2.7	1.7	0.3	0.07
silica in total flow	mg/s	1326	1326	743	498	101	35
	ppm	7.5	7.5	4.2	2.8	0.6	0.2
silica in liquid	mg/s	1195	1198.2	698.5	455.2	85.1	20.0
	ppm	991	967	338	325	123	118
silica in steam	mg/s	131	127	44	43	16	15
	ppm	0.74	0.72	0.25	0.24	0.09	0.09

Table 8: Modelling Results with Wash Water

Table 9 summarises the key modelled data for comparison against the measured values in Table 7. Values that differ significantly are highlighted in the yellow cells. It is worth noting that CDPs 3, 4, and 5 drain to a common flow line which is metered; some individual CDP flow rates were estimated by rate of level rise (based on known pot diameter and, thus, cross sectional area).

Drain ID	Flow Rate (kg/s)	[Cl-]* (ppm)	[SiO₂]* (ppm)	Comment
CDP 1	nil	940	1298	flooded
CDP 2	nil	915	1266	flooded
	1.74	wash water injection		
CDP 3	1.72	299	443	
CDP 4	0.75	286	425	
	1.74	wash water injection		
CDP 5	3.24	102	160	
CDPs 3-5	5.72	186	280	aggregate
Scrubber	0.56	98	155	
Steam	175.2	0.07	0.20	

* as flashed to atmosphere (but flows are metered at line pressure)

Table 9: Modelled Results Summary (with Wash Water)

Modelling was not able to match the individual CDP impurity levels, but it did match the combined flow from all three drain points. There may be errors with the flow rates for individual CDPs, or the wash water spray may not be "captured" in the liquid phase present in the line before CDP3; that would reduce the effective liquid flow at CDP3 and would elevate the impurity levels. And the flow at CDP4 would be correspondingly higher with lower impurity levels. This is shown Table 10 where the wash water injected at the start of section 3 was assumed to be split 30:70 between sections 3 and 4, and pot efficiencies were adjusted to match the measured drain pot flow rates.

Drain ID	Flow Rate (kg/s)	[Cl-]* (ppm)	[SiO_2]* (ppm)	Comment
CDP 1	nil	940	1298	flooded
CDP 2	nil	915	1267	flooded
	1.74	wash water injection		
CDP 3	1.90	555	799	30% wash
CDP 4	1.23	55	139	70% wash
	1.74	wash water injection		
CDP 5	2.59	4	17	
CDPs 3-5	5.72	198	303	aggregate
Scrubber	0.14	4	15	
Steam	175	0.001	0.01	

* as flashed to atmosphere (but flows are metered at line pressure)

Table 10: Adjusted Modelling (with Wash Water)

This highlights the importance of being able to measure flow rates and take samples at each CDP as noted in Section 2.7. (The plant testing was done to assess (i) separator performance and (ii) steam purity at the scrubber outlet; the individual CDP flow and impurity values were not required to achieve those two objectives. The test data are used here to demonstrate the principles of steam purity modelling.)

3.3 Plant X

Readers are challenged to utilise the methodology presented above and use actual test data to develop a purity model for comparison with the observed data, preferably for both chloride ion and silica. The warnings about care in measuring flow rate and concentrations at each drain point, and ensuring drain flows do not contaminate the cooling circuit, should be taken into account. Feel free to contact the authors for assistance if required.

4. CONCLUSION

Steam purity continues to be a key factor in geothermal power plant operation, especially for steam turbine units and combined cycle installations, across the range of resource conditions from two phase to dry steam.

Steamfield designers are often expected to predict the degree of purity of geothermal steam delivered to the power plant before the plant is built, contractors are expected to demonstrate that contract limits are met at commissioning, and operators are keenly interested in monitoring delivered steam purity on an on-going basis.

Valuable insights on the performance of the overall steam conditioning and delivery system (two phase fluid separation, steam line scrubbing, and final scrubbing/demisting) can be derived from performance testing measurements taken for separators and/or scrubbers, provided time is taken to carefully collect and analyse the relevant data. Collecting the data is straight-forward, and readily repeated,

Developing a steam purity model will assist in understanding the process conditions, including heat and mass transfer, within the steam line. The authors advocate taking flow rate, chloride ion and silica concentrations at each drain point in the steam system, plus steam at the scrubber outlet, and analysing the data by means of a steam purity model to better understand the chemical interactions occurring within the steam conditioning and delivery system.

It was easy enough to match chloride ion concentrations at successive drain points, but silica was less well-matched. It may be that silica levels in condensate formed in the line had not reached chemical equilibrium, suggesting that in any given section of line allowance may be required for non-equilibrium concentrations of silica in the liquid phase. Spraying of wash water into the line may provide more favourable conditions for absorbing volatile silica into the liquid phase, as noted by Richardson et. al. (2013). Even though full absorption of silica appears to occur over several sections of line, especially where wash water is sprayed in, greater detail of individual drain flows and silica concentrations would be useful. (In the cases presented for Plants A and B several CDP flows were combined in a single stream that was metered, and individual CDP flows were estimated.) Comparing actual data to modelling predictions should reveal circumstances where attainment of chemical equilibrium of silica between steam and liquid components of the flow can be demonstrated and/or how to account for non-equilibrium distribution.

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