GEOTHERMAL STEAM TURBINE DEPOSITION FUNDAMENTALS AND PROPOSED IAPWS GEOTHERMAL STEAM PURITY LIMITS

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Keywords: *steam turbine, steam purity, deposition, scaling, corrosion.*

ABSTRACT

Geothermal steam turbines are prone to forming significant turbine mineral deposits under suboptimal steam purity and quality conditions. These deposits can then lead to operational and maintenance issues that are detrimental to turbine performance, reliability and availability

The mechanisms related to how deposits form within geothermal steam turbines are discussed in relation to both vaporous and mechanical transport of impurities in steam. Saturated and Superheated steam conditions and their impact on deposition within a geothermal turbine are reviewed. The formation and behavior of the liquid films that form within geothermal steam turbines are outlined and the impact on these liquid films by reheating due to heat transfer across a turbine disk or shaft is discussed.

1. NEED FOR STEAM PURITY LIMITS FOR GEOTHERMAL STEAM TURBINES

1.1 History and Lack of Guidance

The International Association for the Properties of Water and Steam (IAPWS www.iapws.org) has recently issued a series of Technical Guidance Documents (TGD) for the water/steam chemistry control of conventional fossil, industrial and combined cycle plants.[1,2,3,4]. Of specific note is the IAPWS Steam Purity Technical Guidance Document[5], which outlines the key aspects of steam purity for the safe, reliable and efficient operation of fossil, industrial and nuclear steam turbines (saturated steam and superheated steam turbines) and provides a detailed description of the process involved in deposition and corrosion within steam turbines.

This IAPWS document provides the most current industry steam purity limits for superheated and saturated steam turbines as shown in **Figure 1**.

5.1.1 Condensing Turbines with Superheated Steam

Parameter	Unit	Normal / Target Values
Conductivity after cation exchange @ 25 °C	µS/cm	< 0.20
Sodium as Na	µg/kg	< 2
Silica as SiO_2	µg/kg	<10

Table 1. Steam purity for condensing utility turbines with superheated steam, applicable for steam temperature below 600 °C.

5.1.2 Condensing Turbines with Saturated Steam

Parameter	Unit	Normal / Target Values
Conductivity after cation exchange @ 25 °C	µS/cm	< 0.30

Table 2. Steam purity for condensing utility turbines with saturated steam without reheat.

In the event that the steam dries locally, e.g. by expansion in the turbine inlet valve, the specification for superheated steam should be used.

Figure 1: IAPWS Steam Purity Limits*/ for Condensing Steam Turbines (Superheated and Saturated Steam)[6]**

*1 µg/kg = 1 part per billion (ppb) = 0.001 part per million (ppm)

** Conductivity after Cation Exchange is a measure of the electrical conductivity due to anions only in a solution

These limits have been developed from years of operation of fossil, industrial and nuclear steam turbines and extensive

Proceedings 42nd New Zealand Geothermal Workshop
24-26 November 2020
Waitangi, New Zealand
ISSN 2703-4275

research in test steam turbine units with the most significant research[7] being undertaken in the former Soviet Union from the 1960's and in the USA in the 1990's via extensive research undertaken by the Electrical Power Research Institute (EPRI)[8]. The limits have been developed and corroborated[9, 10, 11] for minimising deposition and corrosion in steam turbines in both superheated and saturated steam locations in turbines.

There are currently no published industry steam purity limits available for geothermal steam turbines. Whilst the IAPWS TGD has a specific section discussing geothermal steam turbines[12], no specific steam purity limits are included. Currently, the only technical water/steam guidance specifically for geothermal turbines available internationally is from turbine vendors with the guidance broadly consistent between the different suppliers, but significantly higher than IAPWS fossil, nuclear and industrial steam turbine limits as can be seen in **Table 1**.

Table 1: Summary of Example Geothermal Steam Turbine Manufacturers Steam Purity Limits

Parameter	Toshiba Limits	Fuji Limits	MHI Limits	GE Limit	IAPWS Fossil, Nuclear and Industrial Limit (superheated and saturated steam)
Total Solids	< 0.5 mg/L	< 0.5 mg/L	< 0.5 mg/L	< 0.5 mg/L	N/A
Chloride	< 0.1 mg/L	< 0.1 mg/L	< 0.1 mg/L	< 0.3 mg/L	< 0.002 mg/L
Silica	< 0.1 mg/L	< 0.1 mg/L	< 0.1 mg/L	< 0.3 mg/L	< 0.01 mg/L
Iron	< 0.1 mg/L	< 0.1mg/L	< 0.1 mg/L	< 0.1 mg/L	N/A
Sodium	N/A	< 0.1 mg/L	N/A	N/A	< 0.002 mg/L
Conductivity after Cation Exchange (CACE)	N/A	N/A	N/A	N/A	< 0.2 µs/cm
Sulphate	N/A	< 0.1 mg/L	N/A	< 0.1 mg/L	< 0.002 mg/L

An IAPWS working group made up of members of the Power Cycle Chemistry (PCC) and the Industrial Requirements and Solutions (IRS) groups led by members of the New Zealand and Japanese branches of IAPWS, the New Zealand Association for the Properties of Water and Steam (NZAPWS) and Japan Association for the Properties of Water and Steam (JPAPWS) has been collaboratively working together since 2017 to ensure a complete understanding of the deposition mechanisms in geothermal steam turbines and to develop specific steam purity guidelines for geothermal power plants. This is intended to be released as a future IAPWS Technical Guidance Document.

This paper provides a preliminary summary of that work along with provisional, proposed, geothermal steam turbine steam purity and wash water purity limits. These limits, based on the project activities and actual operating experiences, have been developed to minimize unwanted mineral deposition in geothermal steam turbines, improve steam turbine performance, optimize maintenance costs and to lower the associated corrosion risks associated with corrosive mineral deposits.

2. PROPERTIES OF STEAM RELEVANT TO GEOTHERMAL POWER PLANTS

2.1 Geothermal Steam Use in Geothermal Power Plants

In direct contact geothermal power plants, the geothermal water/steam mixtures are extracted from the ground via production wells, the bulk of the fluid is separated and the steam is directed into a steam turbine to be converted into electrical energy.

A direct contact geothermal power plant is shown in **Figure 2** and is comprised of the following main components:

- A production well to extract the hot, pressurised water/steam mixture from the Earth to the surface.
- A water/steam separator to extract the saturated steam from the bulk of the water phase and to direct the extracted water or brine back to an injection well (not required for dry steam wells)
- Steam lines to transport the saturated steam to the steam turbine. These steam lines will often include additional moisture removal and steam scrubbing equipment including steam washing systems involving wash water injection.
- A steam turbine and generator to transfer energy from the steam into electrical energy.
- A gas extraction system to remove non-condensable gases such as carbon dioxide and hydrogen sulphide from the system
- A condenser after the steam turbine to cool the remaining steam and condense it fully back into water.
- A cooling tower to remove residual heat from the condensed geothermal steam prior to its return to an injection well unless a once through cooling system is utilized.

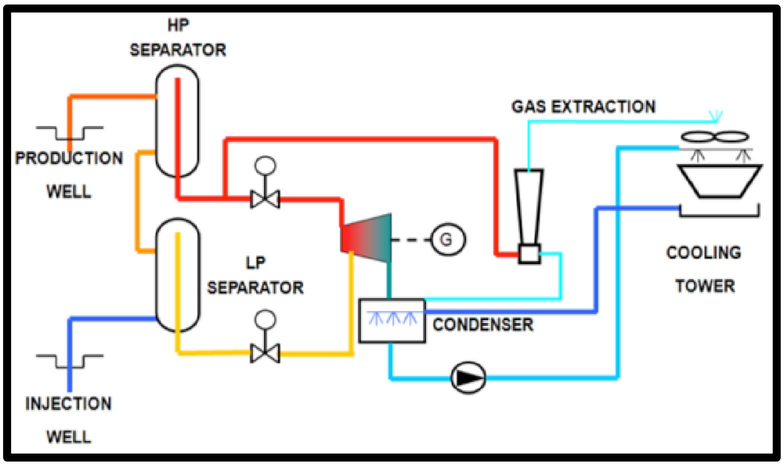

Figure 2: A Direct Contact Geothermal Power Plant Basic Schematic From Production Well to Injection Well

2.2 Transport of Dissolved and Entrained Ions, Minerals and Oxides in Geothermal Steam

In the case of geothermal power plants with direct contact steam turbines, there are two mechanisms for the transportation of impurities (contaminants) in geothermal steam:

- Mechanical Transport and
- Vaporous Transport

Even with the differences in direct contact geothermal power plant steam chemistry compared to fossil, industrial or nuclear plants, such as the presence of hydrogen sulfide and carbon dioxide gases in geothermal steam, the same fundamental scientific principles apply related to the transport of impurities in steam.

2.3 Mechanical Transport

Mechanical carryover is the entrainment of water droplets in steam exiting a geothermal water/steam separator[13]. In the case of direct contact geothermal power plants, the entrapped water droplets are of the geothermal brine. The amount of mechanical carryover depends on the physical design and mechanical condition of the water/steam separators, level control within the separator, and steady-state operating conditions (pressure and flow). Mechanical carryover is a function of the density difference between water and steam phases at a particular operating pressure. In the operating ranges common to geothermal power plants, the density of water, relative to steam, decreases with increasing temperature and pressure and mechanical carryover becomes more likely/severe.

Mechanical carryover/transport can also occur with solid particles being transported in saturated steam either as discrete solid particles or via particulates within the steam entrained water droplets. In the case of direct contact geothermal power plants, these solid particles can include formation material transported up from the production wells and corrosion products from the corrosion of well tubulars, pipelines, separators and steam line internal surfaces[14].

If water droplets are entrained in geothermal steam after a separator, then moisture removal system(s) are required to attempt to remove the droplets prior to entry to a steam turbine[15].

If the saturated steam is then heated further, it will become superheated with some of the dissolved ions in the water phase becoming soluble in the superheated steam and others precipitating as solids (dusts) and being physically transported in the steam.

2.4 Vaporous Transport

Vaporous carryover occurs due to the inherent volatility of the compounds present in the geothermal fluids as a function of temperature and pressure. Molecular impurities present in geothermal fluids can evaporate with steam under suitable temperature and pressure conditions. The key example of this in geothermal plants is silica that can be transported via vaporous carryover under certain conditions[13].

The degree of vaporous carryover is expressed as a distribution ratio of the concentration of the compound or impurities in the steam to that in the geothermal brine at a given pressure. The distribution ratio is a function of:

- separator pressure and temperature,
- geothermal brine dissolved solids concentrations, and
- brine pH and interactions between the species present.

2.5 Primary Sources of Dissolved and Entrained Ions, Minerals and Oxides in Geothermal Steam

In the case of geothermal turbines operating on saturated steam, the primary source of contaminants that enter the steam turbine and that can result in deposition and corrosion within the steam turbine is mechanical carryover of brine from the separator vessels. Vaporous carryover of silica can also occur but is less common in lower operating pressure plants.

The transport of solid particles in saturated steam can also contribute to contaminants entering the turbine leading to turbine deposits.

Because the steam is saturated a liquid condensation layer is present on the pipe and vessel walls of the steam touched surfaces. When contaminants are present in the bulk steam due to mechanical or vaporous carryover these contaminants will preferentially partition into the liquid phase and increase in concentration. The concentration of contaminants in the liquid condensation layer can be up to ten times that of the bulk steam concentration. An example of this phenomena is shown in **Figure 3**

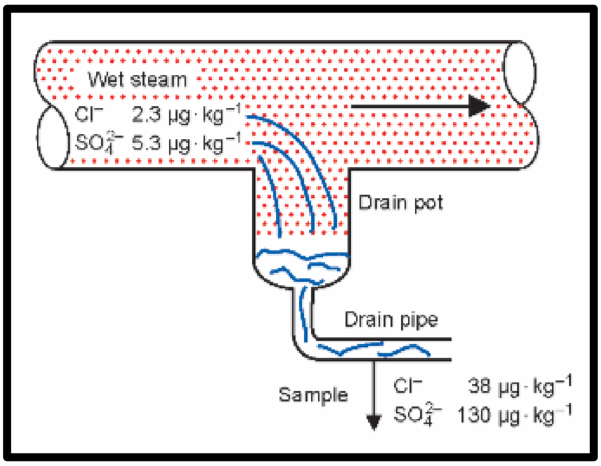

Figure 3: Concentration of impurities in the drain of a wet steam pipe[10]

This concentration process can be accelerated in geothermal steam lines with the injection of steam washing water then followed by the removal of the condensate via a scrubber or drain pot and then a repeat of wash water injection followed by further condensate removal. This process should incrementally improve the steam purity as contaminants are removed from the bulk steam via the drain systems.

In the case of steam line scrubbing systems, the normal water supply for scrubbing is condensed geothermal steam supplied from the cooling water system. This water may contain dissolved ions, including dissolved oxygen (if a direct contact condenser is in use) that, if not effectively removed, will contribute to deposition and corrosion within a geothermal steam turbine.

Ineffective or poorly maintained or operated moisture removal systems (MRS[16]) downstream of the separator vessels combined with low drain pot efficiency[17] and low purity wash water will result in steam contaminants remaining in the bulk steam or in a remaining condensate layer. At the point of entry to a steam turbine the bulk steam and remaining, un-removed condensate layer will be re-homogenized through the control valves and the steam purity of the steam entering the steam turbine will be poor.

3. INTRODUCTION TO STEAM TURBINES FOR GEOTHERMAL ELECTRICITY GENERATION

As discussed in Section 2.1 once the geothermal steam is extracted from the production well and separated and then transported with moisture removal it is then supplied to a steam turbine. An example of an operational geothermal steam turbine is shown in **Figure 4**

Figure 4: Geothermal Direct Contact Steam Turbine

A steam turbine converts moving steam to mechanical energy aerodynamically, through a circular arrangement of stationary and rotating airfoils (blades) attached to a central shaft or rotor. Each stationary and rotating row set is called a “stage.” The stationary blades direct the steam into the rotating blades. Lift on the rotating blades turns the rotor of the steam turbine and this then spins the generator attached to the steam turbine and generates electrical power. These may be impulse or reaction blades

As steam moves through a steam turbine, the energy in the steam, present as temperature and pressure, decreases as that energy is transferred to the steam turbine and converted into rotational force. Therefore, the steam is in a lower energy state, as it exits the stream turbine with a lower temperature and pressure than when it entered.

4. FORMATION OF LIQUID FILMS AND MINERAL DEPOSITS IN GEOTHERMAL STEAM TURBINES

The IAPWS Technical Guidance Document– Steam Purity for Turbine Operation, provides a succinct description of the mechanisms involved in the formation of water droplets and liquid films from superheated steam in steam turbines. In the case of saturated steam turbines, the steam enters the turbine with water droplets already present, so the initial nucleation of early condensate, as described in the IAPWS TGD has in a sense already occurred.

For saturated steam turbines, liquid films form on the steam turbine materials as the steam flows through the turbine. These films can be up to 100-120 μm in thickness[18] and form either by collision of the liquid droplets or by heterogeneous nucleation from the steam on the blade/disk material itself. In the case of geothermal steam turbines with the steam entering the turbine in a saturated state impactions of water droplets onto the steam turbine surfaces will likely further increase the thickness of the liquid films. If vaporous contaminants such as silica are present in the steam, then these will also condense into the liquid phase and become part of a liquid film as the pressure drop in the steam turbine occurs[13]. These liquid films may be subject to reheating due to heat transfer across a turbine disk or shaft which results in concentration of ionic impurities by up to a factor of about 1000 times the levels found in the bulk steam[19].

4.1 Influence of Steam Purity on Liquid Films in Geothermal Steam Turbines

In the case of 100% pure saturated steam, containing only pure water vapor and pure water droplets with no other ionic contaminants present, a liquid film formed on a steam turbine surface will be made up of only pure water. As the purity of the steam decreases (due to increasing levels of contaminants), the purity of the liquid film will also decrease.

4.2 Steam Turbine Reheating

Reheat energy is present in the turbine due to friction of the rotating turbine materials and from stagnant steam flow areas within the turbine where windage or reheating is occurring[20]. As reheating occurs within the liquid film on the turbine surfaces, water vapor leaves the film whilst the dissolved ionic impurities remain. As this process continues the concentrations of the ionic impurities in the liquid film increase until they exceed their solubility limits at the conditions that the turbine is operating under. Precipitation, as solid deposits, of the ionic impurities onto the turbine surfaces then occurs. This is a continuous process with the turbine in operation with a continuous input of additional water droplets and the associated ionic impurities to the liquid film which then, due to reheating, continues the concentration and precipitation process. On shutdown the remaining liquid film fully evaporates leaving a mineral deposit on the surfaces[10] as can be seen in **Figure 5**.

Figure 5: Example of Significant Geothermal Steam Turbine Deposits on a 1st Stage Stationary Blade/Nozzle Due to Reheating of a Turbine Liquid Film and Suboptimal Steam Purity Conditions

4.3 Enthalpy-Entropy (Mollier) Diagrams

An Enthalpy-Entropy diagram, also known as a Mollier Diagram in the context of steam turbines, provides a representation of the thermophysical conditions of steam within the steam turbine as energy is extracted from the steam and converted to mechanical energy (rotational energy). An example of a Mollier Diagram[21] is shown in **Figure 6**.

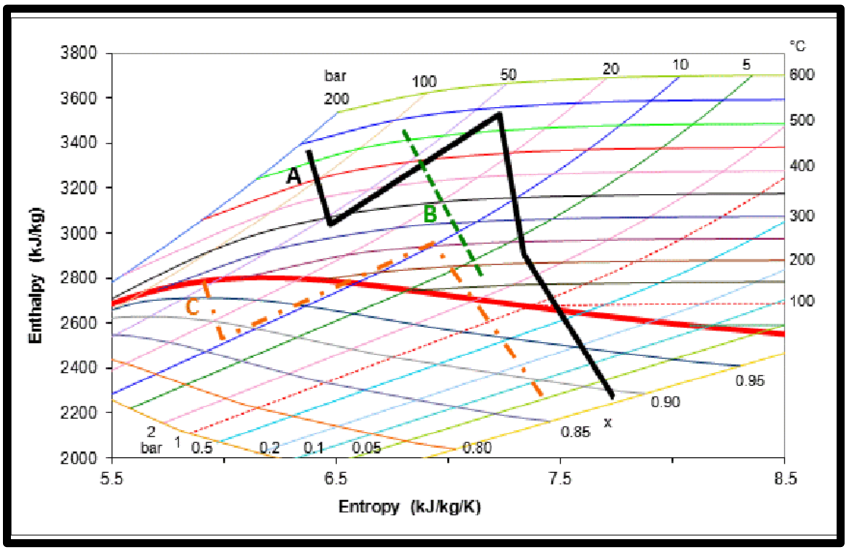

Figure 6: Mollier diagram with three typical turbine cycles (symbolic presentation): A = reheat turbine in fossil fired plant, B = backpressure turbine, C = reheat turbine in a nuclear light water reactor plant

This diagram shows three hypothetical steam turbine designs with differing steam conditions. The bold red line shows the boundary between superheated (above the line) and saturated steam (below the line) conditions. This is known as the Saturation Line. Lines A, B and C show the changes in pressure, temperature, enthalpy and entropy of the steam as it passes through various stages of different steam turbine designs and in the case of A and C additional reheat energy is added into the steam external to the steam turbine (via a reheater).

As steam moves through a steam turbine the energy in the steam, present as temperature and pressure, decreases as that energy is transferred to the steam turbine and converted into rotational force. Therefore, the steam as it exits the steam turbine, is in a lower energy state with a lower temperature and pressure than when it entered the steam turbine. This means that the Enthalpy of the steam decreases while the Entropy increases. This also means that the moisture content of the steam increases as the steam condenses as it moves through the steam turbine doing work.

For line A (the black line), which represents a conventional fossil steam turbine operating under superheated steam conditions at the entry to the turbine and with a reheater, the point that the line crosses the saturation (red) line is where the steam goes from superheated to saturated. and Phase Transition Zone or PTZ beginning. The PTZ is considered to extend downward from the saturation line until, for example, for fossil steam turbines, the steam is approximal 9-11% moisture.

For line B (the green line) this represents a superheated steam back pressure steam turbine where the steam enters and exits the steam turbine still in a superheated condition.

For line C (the orange line) this represents a nuclear power plant reheat turbine where the initial entry of steam to a multiple stage turbine is saturated, as in a geothermal power plant. The steam is extracted from the first stage turbine, then additional heat energy is provided via a reheater which superheats the steam, and then the superheated steam re-enters the steam turbine into a low pressure stage. As the steam moves through the low pressure stage it crosses the saturation line and becomes saturated before finally exiting the steam turbine. Line C can be considered to be the closest to what occurs in a geothermal steam turbine.

A saturated steam geothermal turbine would be expected to have a Mollier diagram showing the steam turbine entry conditions for the steam below the red (saturation) line with the steam conditions become progressively more and more saturated (moisture containing) as the steam flows through the steam turbine, work is extracted and the steam is condensed.

An example of a Mollier diagram for a direct contract geothermal steam turbine (Enthalpy-Entropy) is shown in **Figure 7** for conditions where the IP and LP steam inlet conditions are only just saturated. This situation means that a very small amount of heat transfer across the turbine disk would be required to result in reheating of the liquid film that is formed on the blade surfaces in the first few rows of the steam turbine with the resulting concentration of any ionic impurities present in that liquid film. As the steam then moves through the steam turbine the moisture content of the steam would continue to increase.

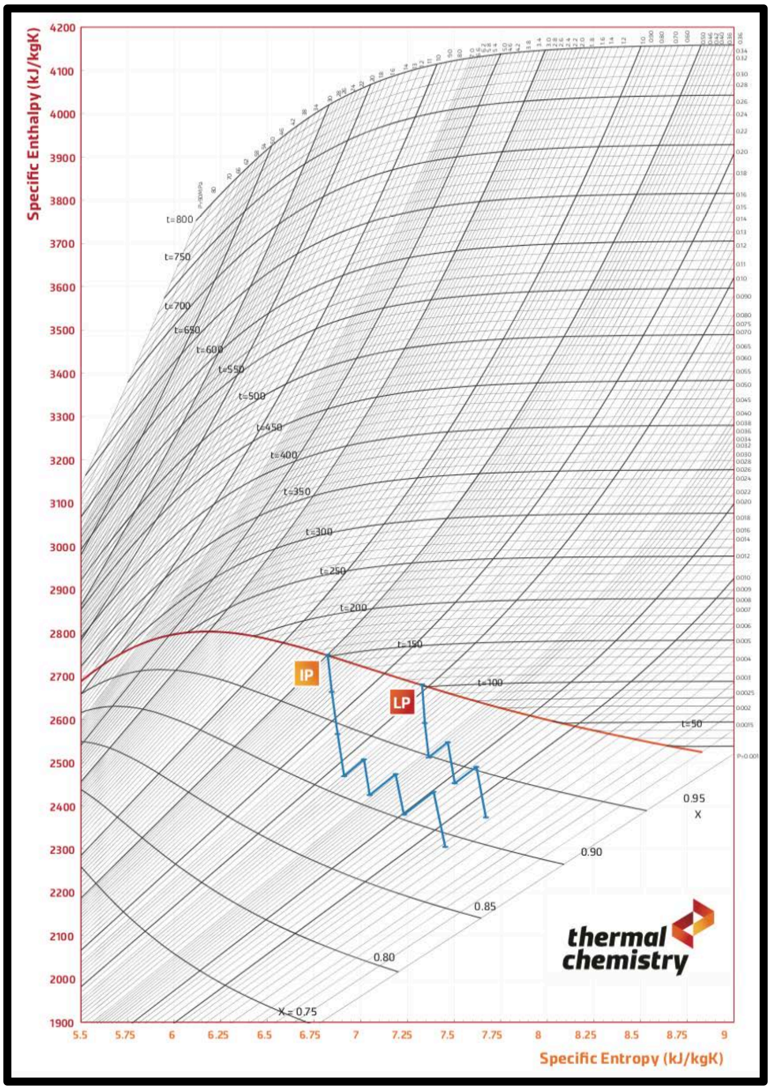

Figure 7: Geothermal Two Pressure Steam Turbine Mollier Diagram (Bold Red Line = Saturation Line

4.4 Impact of Superheating of Geothermal Saturated Steam

Superheated steam is steam at temperatures higher than its boiling point for its pressure, which only occurs when all liquid water droplets present in the saturated steam have evaporated to form more steam. The formation of superheated steam involves the input of additional heat energy to saturated steam. Superheated steam contains only one phase – water vapor (steam) and has no water droplets present in it. It is also known as "dry" steam.

As superheated steam enters a fossil, industrial or nuclear low pressure (LP) turbine and expands, as per Line A in **Figure 6** it approaches and crosses the saturation line where droplets of moisture are nucleated heterogeneously on ions. This is known as the phase transition zone (PTZ), where the expansion and cooling of the steam leads to condensation. In many geothermal plants, the steam is never superheated and enters the steam turbine already in a saturated state, with a dryness factor < 100%. Therefore, there will not be a saturation line in the turbine.

However, if there is throttling across the turbine inlet control valves this pressure drop may result in slight superheating of the incoming steam due to the additional friction energy generated across the valve opening[16]. If this occurs all saturated steam water phase contaminants will become either soluble in the superheated steam or precipitate as solid particles either within the valve or as small particles entrapped in the steam. In this case, because the degree of superheat will be very low (i.e. only one to two degrees of superheat), the superheated steam will almost immediately re-cross the saturation line and enter the PTZ as the initial pressure drop occurs in the first stage of the steam turbine section.

The solubility of contaminants/solutes in steam is dependent on the steam pressure and temperature (typically solute solubility increases with increasing pressure, and also increases with increasing temperature). During superheating of steam, the solubility of solutes in the steam will decrease, due to the decrease in steam pressure, while any solutes contained in moisture that is then evaporated will be either dissolved in the steam (if unsaturated), or precipitate as a solid. When superheated steam becomes saturated, most solutes dissolved in the steam will preferentially partition into the liquid (water) phase where the concentration will become significantly higher than the bulk steam concentration, determined by the partitioning coefficient for the particular solute. If this moisture containing the elevated levels of solute is subsequently evaporated due to reheating, precipitation of the solutes contained within the liquid is expected to occur at a rate faster than would be expected with just saturated steam only.

In the case of a geothermal steam turbine operating with superheated steam with a PTZ part way through a steam turbine, where there is the transport of solid particles in the steam, deposition onto the turbine can also occur by impaction in the dry sections of the turbine prior to the formation of liquid films in the turbine as well in the wet section of the turbine.

A number of processes that take place in the PTZ (i.e. precipitation of chemical compounds from superheated steam, deposition, evaporation, and drying of liquid films on hot surfaces) can lead to the formation of surface deposits that are potentially corrosive and that disrupt the steam flow across the stationary blades and so impact the steam turbine performance. This results in a reduction of the flow passing ability ("swallowing capacity") of the turbine and a change in the effective steam flow profile on the turbine blades. These changes result in a reduction of steam flow and consequently power output of the turbine, and a degradation of turbine efficiency[22].

Industry experience has shown that when superheating has occurred in geothermal steam turbines the rate of deposition is accelerated significantly because of the changes in solubility of the superheated and saturated steam and the decreased volume of water in the liquid film in the first rows of blades in the steam turbine. An example of this is shown in **Figure 8.** Superheated steam operation of geothermal steam turbines should be avoided unless the steam purity is high.

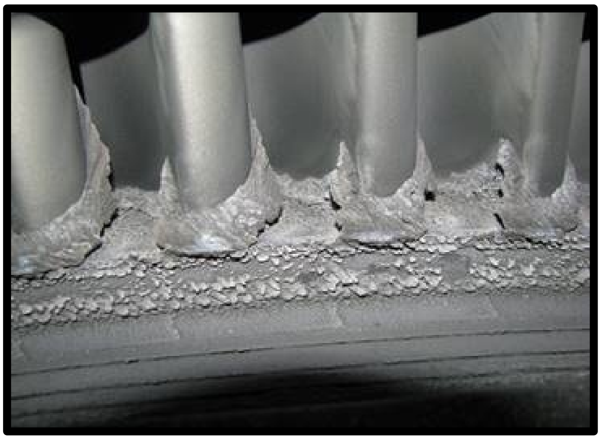

Figure 8: A Example of Inadvertent Superheated Steam Operation of a Geothermal Steam Turbine Leading to Rapid and Heavy Deposition

5. CHEMISTRY RELATED DAMAGE MECHANISMS IN STEAM TURBINES

5.1 Deposits

Once a liquid film is formed and if there is sufficient reheat energy present, water vapor leaves the film via evaporation whilst the dissolved ionic impurities remain.

This is a continuous process with the turbine in operation with a continuous input of additional water droplets and the associated ionic impurities to the liquid film which then, due to reheating, continues the concentration and precipitation process. On shutdown the remaining liquid film fully evaporates leaving a solid mineral deposit on the surfaces[10].

Under these conditions the rate of deposition in a geothermal steam turbine depends on the following:

1. The degree of reheating occurring in the steam turbine.

2. The amount of moisture present in the saturated steam (the steam quality).

3. The mass flow of steam through the steam turbine.

4. The concentration of various ions in the water phase of the steam (the steam purity).

The use or otherwise of steam washing systems and/or steam turbine washing systems also have an influence on factors (2) and (4).

The locations of deposits under these conditions will be dependent on the amount of moisture present in the steam and the reheat energy available at a given location within the steam turbine. The moisture content is lowest in the steam entering the steam turbine, and therefore this steam requires the least amount of reheating energy from the turbine itself to commence the evaporation and concentration process. The moisture content of the steam increases as it flows through the turbine. This increasing amount of moisture as the steam moves through the steam turbine can been seen in the Mollier Diagram in **Figure 6** as the enthalpy decreases and the entropy increases below the saturation line. This increased moisture content dilutes the ionic impurities and decreases their concentration so that the evaporation and concentration process followed by precipitation no longer occurs to a meaningful level.

For deposits to occur on a steam turbine it requires the ions in question to be transported in the steam, either solubilised in the steam or as solid salt crystals, into the turbine to provide the "source" of the deposits. These ions are transported by saturated or superheated steam via the transport mechanisms as already discussed (Section 2.3 and Section 2.4). Solid particle deposition as discussed, can also occur in both saturated steam (formation material and corrosion products from upstream surfaces) and superheated steam (precipitation of contaminants as salt crystals).

5.2 Corrosion Related Damage Mechanisms in Steam Turbines

The IAPWS Technical Guidance Document– Steam Purity for Turbine Operation provides a succinct description of the damage mechanisms involved with corrosion within steam turbines. This key information has been summarised and adjusted for relevance for geothermal steam turbines and is as follows.

The initiation of corrosion normally takes place in a steam turbine after a deposit has been formed that can result in a corrosive environment being formed on the turbine surfaces. This is normally in conjunction with an offline environment that contains moisture and high levels of oxygen. Normally a chloride, hydroxide or sulphate deposit is required to react with moisture and oxygen, which then initiates pitting on the steam turbine surfaces when the turbine is shutdown.

Pitting and localized corrosion are critical precursors to more extensive damage from Corrosion Fatigue (CF) and Stress Corrosion Cracking (SCC)[23], although extensive pitting of blades can cause significant loss of stage efficiency due to the disruption in surface smoothness or, in extreme cases, weaken component integrity to the point of mechanical failure.

Pitting and localized corrosion are unlikely to originate during turbine operation due to the absence of oxygen in the liquid films on the turbine surfaces during operation. Rather, pitting results from corrosive deposits absorbing moist air during turbine shutdown. However, there are some industry indications in geothermal steam turbines that pitting corrosion may occur online due to hydrogen sulphide with oxygen present from the injection of oxygenated wash water being but no detailed scientific data has been published on this at the time of writing.

During non-protected shutdowns where the blade/disk surfaces are open to the atmosphere, any deposits, particularly chloride or sulfate, which have formed on steam-path surfaces during operation can become moist and lead to local, conductive, aqueous environments that contain ppm levels of oxygen. These local environments initially lead to breakdown of the blade metal passivity, then to metastable pit formation, and finally to stable pits after repeated shutdown cycles. Each shutdown period is followed by operation where the dynamic situation of droplet formation, liquid films and deposition occur.

Most often, these pits are not visible, but because they have resulted from an active corrosion mechanism during shutdown the internal surfaces will be rather irregular due to passivity breakdown. The different environments which exist during the repetitive operation and shutdown periods eventually lead to the initiation and growth of a number of pits on the surface.

Corrosion Fatigue (CF) and Stress Corrosion Cracking (SCC) of turbine components have been consistently identified among the main causes of turbine unavailability. Both phenomena are characterized by two stages: initiation and propagation.

In steam turbines, initiation most frequently occurs at microcracks that emanate from pits that form when deposits become corrosive during unprotected shutdowns. Cracks can, however, also initiate on locations of fretting, manufacturing defects, inclusions, microscopic imperfections, and at areas where specific absorption of species has locally reduced surface energy. These locations are where deposition will be preferential. Increased surface roughness acts to increase deposition.

Propagation of CF and SCC is driven by cyclic or steady stress situations only in regions where dynamic liquid films are present.

5.3 Mechanical Related Damage Mechanisms in Steam Turbines

There are multiple mechanical damage possibilities for a steam turbine but the relevant ones related to steam turbine deposits due to suboptimal steam purity include mechanical blockages, plugging of steam flow paths and a reduction of flow passing ability ("swallowing capacity") of the steam turbine[24].

Mechanical blockages due to deposits are rare but if present on control valves can result in the valves malfunctioning. Significant deposits can also result in erosion damage to blades and turbine components and the impediment of blade movement if the deposit is heavy enough.

Plugging of the steam flow path due to deposits changes the pressure relations in the turbine in a way that can cause an axial shift of the shaft. This can lead to contact between rotating and stationary parts, with the potential for severe failure. Such conditions are usually detected and avoided by monitoring the turbine pressures, vibration sensors and bearing conditions.

The more common result of steam flow plugging is a reduction of the flow passing ability ("swallowing capacity") of the turbine, and a change in the effective steam flow profile on the turbine blades. These changes result in a reduction of steam flow and consequently power output of the turbine, and a degradation of turbine efficiency.

Foreign material can also enter steam turbines due to mechanical breakage of upstream components (valves etc) but these also require transport in the steam and will normally cause immediate mechanical damage to the steam turbine due to their size and mass and not deposits on the turbine materials.

Removal of turbine deposits can be undertaken by two methods

1. The application of turbine wash water during turbine operation to increase the moisture content of the steam to attempt to wash turbine deposits off the blades. This method is not 100% effective for turbine deposit removal and also increase erosion damage to the turbine due to the increase in steam moisture content. Turbine washing during operation is a common practice for geothermal steam turbines

2. During turbine overhauls the mechanical strip down and cleaning of the turbine blades and surfaces. This is often a annual activity and imposes a significant financial cost.

6. GEOTHERMAL STEAM PURITY LIMITS PROPOSED IAPWS GUIDELINE VALUES

Table 1 and **Table 2** have been developed as preliminary, proposed IAPWS geothermal saturated steam purity limits by the IAPWS working group to try to help resolve the deposition and corrosion issues associated with suboptimal steam purity in geothermal steam turbines.

These proposed limits have been shown to be achievable in operating geothermal power plants with effective moisture removal and steam scrubbing systems combined with effective online monitoring of steam purity via sodium and silica analysis.

These limits could, in the future, be used by plant owners in technical specifications to encourage plant designers and constructors to provide steam lines, scrubbers, demisters, steam washing and moisture removal systems that can ensure that the final steam purity supplied to the turbine minimizes deposition and corrosion risks for the plant. This would improve plant efficiencies and lower maintenance costs.

Because the science of steam turbine deposition is the same regardless of steam turbine type these values are essentially aligned with current IAPWS steam purity limits for fossil and nuclear units with the most significant difference being a relaxation of silica limits based on increasing steam pressure and the removal of the Conductivity after Cation Exchange (CACE) limits as this value in geothermal steam is heavily influenced by dissolved, ionizable, gases such as carbon dioxide and hydrogen sulfide.

Table 2: Geothermal Steam Purity Proposed IAPWS Limits

Parameter	Value (Normal Operation)	Online or Grab Sample	Comment
Sodium*	< 2 µg/L	Online	Same as for fossil plants –Saturated Steam
Chloride**	< 2 µg/L	Grab	Same as for fossil plants –Saturated Steam
Silica*	Pressure dependent	Online	As per silica table

* Being effectively measured online at < 1 µg/L detection level levels at New Zealand plants for Sodium and < 5 µg/L detection level for Silica, ** Grab sample only

Based on the solubility of silica in steam at saturation conditions, it may be possible to have a silica in steam limit based on the steam pressure at which the steam becomes sufficiently wet to prevent further dry out - e.g. after the 2nd stage on a saturated steam turbine.

This would result in a limit for silica concentration in steam as per **Table 2** that varies with turbine inlet pressure:

Table 3: Geothermal Steam Purity Proposed IAPWS Silica Limits

Turbine inlet pressure (bar(g))	Silica limit (µg/kg)
<14	**20**
14-17	**30**
17-19	**40**
19-21	**50**
21-23	**60**
23-25	**80**

7. GEOTHERMAL WASH WATER IAPWS PROPOSED LIMITS

High purity wash water for both steam washing (water injection into steam lines) and turbine washing (water injection into steam immediately prior to steam turbine entry) is optimal for minimising downstream corrosion and maximising steam washing capabilities. **Table 3** provides proposed values.

Of note is the dissolved oxygen value of < 10 µg/L. This is to minimise unwanted acid forming reactions between hydrogen sulfide in the steam / iron sulfides that form on steam touched steel surfaces and oxygen resulting in low pH condensate forming and increased carbon steel steam pipework corrosion rates for both the online and offline environments.

Potential water sources for this water include

1. Steam turbine condensate with additional mechanical or gas transfer membrane oxygen removal

2. Demineralised water with additional mechanical or gas transfer membrane oxygen removal

Chemical oxygen scavenging is not recommended due to the slow reaction rates expected at the low temperatures of the wash water.

Table 4: Geothermal Steam Wash Water Purity Proposed IAPWS Limits

Parameter	Value (Normal Operation)	Online or Grab Sample	Comment
Conductivity after Cation Exchange (CACE)	< 0.5 µs/cm	Online analysis	Close to IAPWS demineralised water limits of < 0. 1 µs/cm
Dissolved Oxygen	< 10 µg/L	Online analysis	Similar to IAPWS feedwater dissolved oxygen limits

8. CONCLUSION

The technical understanding of how steam purity influences steam turbine mineral deposits in geothermal steam turbines is well understood based on the various fossil, industrial and nuclear steam turbine studies undertaken over the last 60 years predominantly led by IAPWS members.

The application and customization of this knowledge in relation to both optimized steam purity and wash water purity limits for geothermal steam turbines can help to minimize unwanted mineral deposition and corrosion risks. This will also result in decreased plant maintenance costs and improved operating efficiencies.

The proposed steam purity and wash water limits outlined in this paper are achievable and could be adopted by geothermal steam turbine operators

9. ACKNOWLEDGEMENTS

The authors would like to acknowledge their colleagues in the IAPWS Power Cycle Chemistry and Industrial Requirements and Solutions Working Groups, The New Zealand Association for the Properties of Water and Steam, turbine manufacturers and friendly turbine engineers for the many great discussions over the years related to steam purity, steam chemistry, deposits, corrosion and steam turbines.

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Proceedings 42nd New Zealand Geothermal Workshop
24-26 November 2020
Waitangi, New Zealand
ISSN 2703-4275