INTERNATIONAL ASSOCIATION FOR THE PROPERTIES OF WATER & STEAM

1

Damage and Failure in the Phase Transition Zone (PTZ) of the Steam Turbine, and the Steam Purity Solutions

Barry Dooley – Structural Integrity, UK
Bobby Svoboda – Svoboda Consulting, Switzerland

IAPWS Webinar
31st March 2026

We plan to address questions asked frequently:
1. Why the PTZ, 2. What is the PTZ, 3. What is the environment of PTZ, 4. Why do failures occur here? 5. Do the IAPWS Steam Purity Technical Guidance Documents address the major problems, 6. Can the PTZ move to other blade rows? 7. How important is shutdown protection (DHA), and 8. Are CO_2 and organics important.

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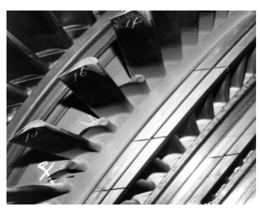
Leading Steam Turbine Damage Mechanisms
(Cycle Chemistry Influenced)

- Corrosion Fatigue of blades and discs in PTZ of LP
- Stress corrosion cracking of discs in PTZ of LP
- Deposition
- Pitting (non-protected shutdowns)
- Copper Deposition in HP *
- Liquid Droplet Erosion
- Flow-accelerated Corrosion+



* Dooley & Shields, PPChem, 2004
\+ Dooley & Lister, PPChem, 2018

LP Low Pressure Turbine
HP High Pressure Turbine
PTZ Phase Transition Zone

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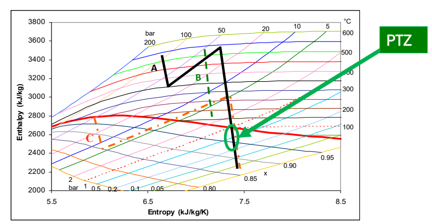
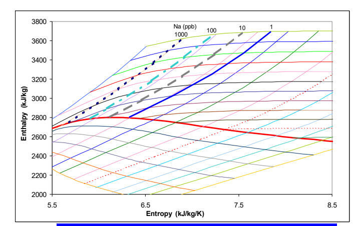
Failures and Deposits in the Phase Transition Zone (PTZ) of Steam Turbines
(Cycle chemistry understanding available since early-1990s)



Mollier diagram with three typical turbine cycles
A.Fossil Reheat Turbine
B. Backpressure Turbine
C. Reheat Turbine in a nuclear LWR plant



Solubility limits of NaCl at various steam conditions

IAPWS Steam Purity TGD 5-13, September 2013
www.IAPWS.org

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A Few Examples of PTZ Failure, Damage and Deposits

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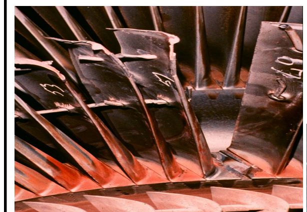
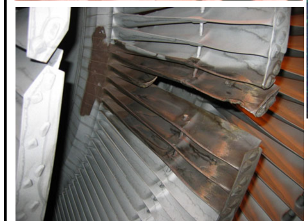
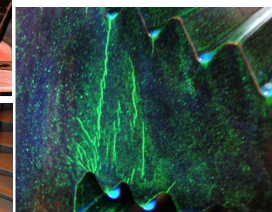
Deposits, Corrosion Fatigue and SCC in the PTZ

Leading Steam Turbine Problems Worldwide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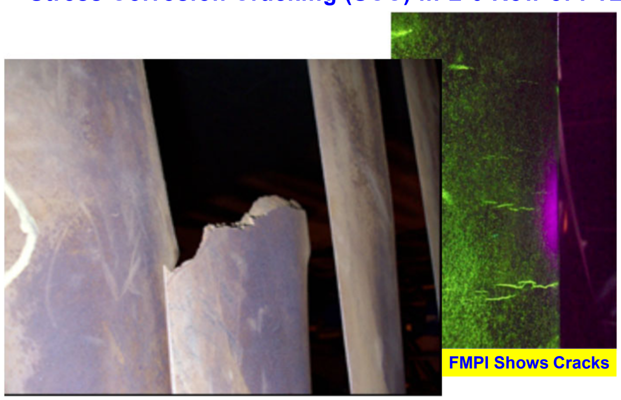
Stress Corrosion Cracking (SCC) in L-0 Row of PTZ



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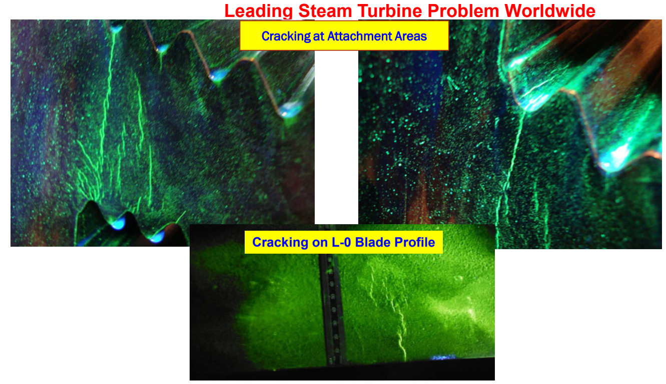
SCC in the PTZ

Leading Steam Turbine Problem Worldwide



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Deposits on Steam Turbine Blades

Sulphate/chloride deposits on LP blades and NaOH deposits on IP blades

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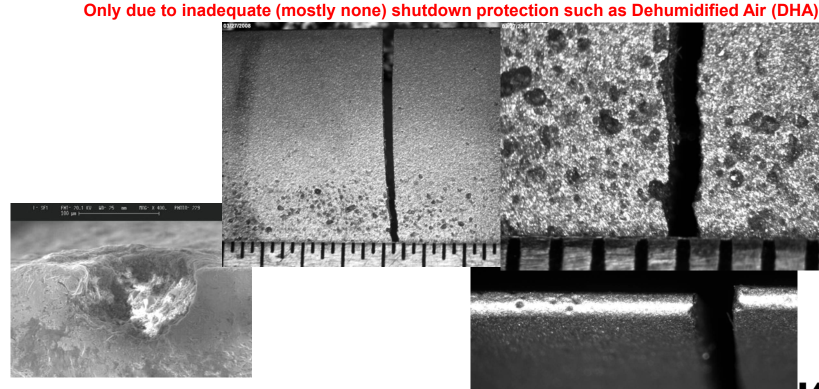
All PTZ Failures Initiate at Pits

Only due to inadequate (mostly none) shutdown protection such as Dehumidified Air (DHA)



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Pits Come in Many Forms

(600MW Once-through Sub-critical Unit operating on OT. LP2 Stage 1 Inlet)
(Benchmark: World Class but with 4 RCCS (includes no shutdown protection)

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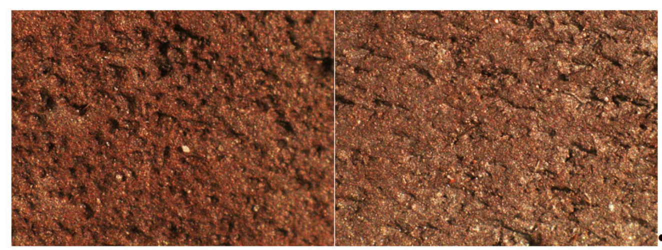
Pits on Pressure and Non-pressure Faces



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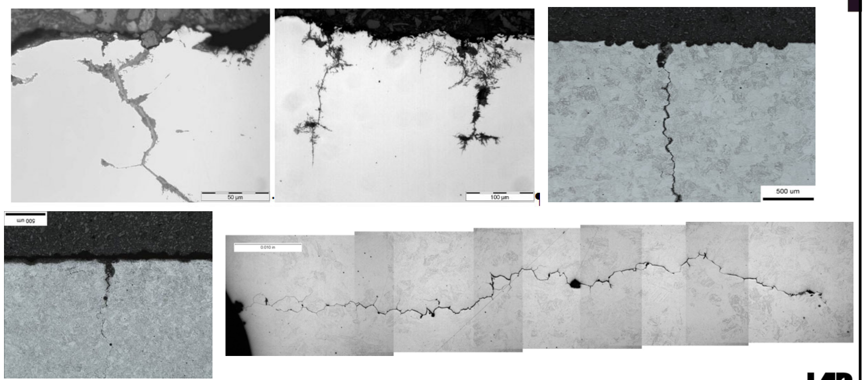
Pitting Leading to Micro-Cracks



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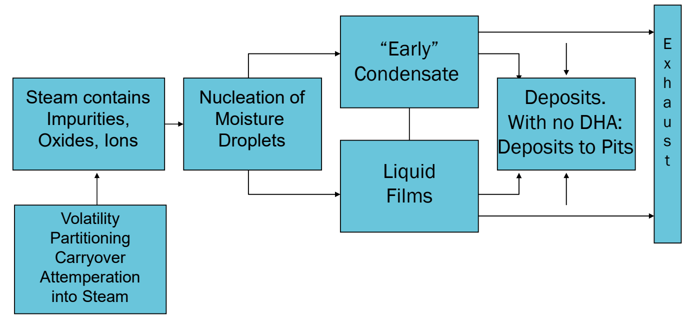
Simplified Dynamic Processes in PTZ



Prior to 1990 many of these processes were not understood and remain that way for many today. Details ⇨

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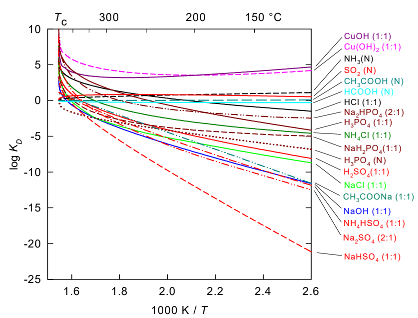
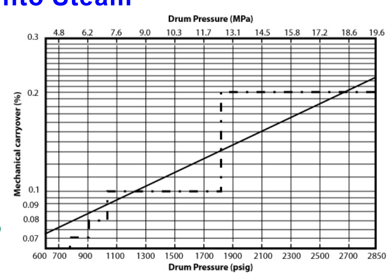
Carryover into Steam





Carryover = Steam Na/ Boiler Na

Volatile Partitioning Constants
Compiled from Palmer and Simonson up to 2004
and "Aqueous Systems at Elevated Temperatures and Pressures". Elsevier, 2004

Mechanical Carryover
IAPWS TGD. TGD1-08.
Should be checked every 6 months or it is a RCCS

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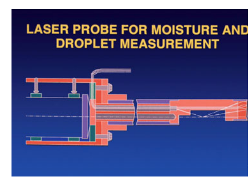
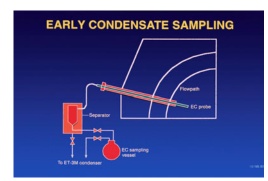
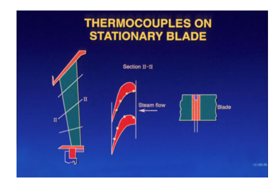
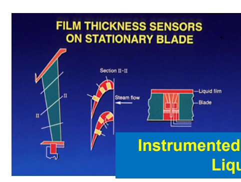
Tools which Monitored the PTZ (1990 – 2005)

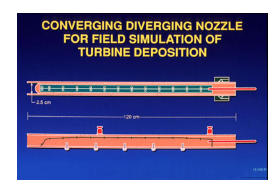








Instrumented Blade to measure Liquid Films



Sources: Martynova/Povarov/Petrova et al 1990s, Jonas, Dooley, EPRI, Dooley/Rieger, 2001. Svoboda/Bodmer, 2004. 23 International Organizations

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Moisture, Early Condensate and Liquid Films in PTZ

Moisture Droplets / Early Condensate

Concentration ratios up to 150 - 200x (not high enough for damage)

Concentrations increase with decreasing moisture

Typical size of droplets 0.1 µm

Droplets influenced by surface tension

Dynamically < 1 ppb O_2 in EC

Liquid Films on PTZ Surfaces

Range up to 100 - 120 µm

Very variable profile on surfaces.

Dependent on chemistry

Concentration factors 10x > EC

<< 1 ppb O_2 in LF

Sources: Martynova/Povarov/Petrova et al 1990s, Dooley, EPRI, Dooley/Rieger, 2001 and Svoboda/Bodmer, 2004

LAP WS

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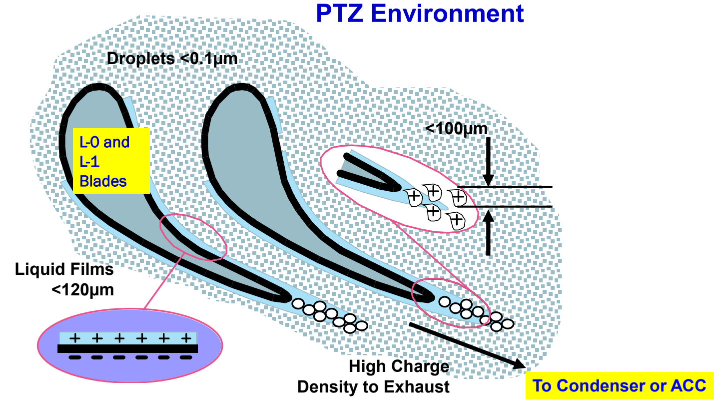
PTZ Environment



Adapted from EPRI, Dooley and Dooley and Rieger, PPChem 2001, 3(5)

LAP WS

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The PTZ Damage and Failure

Overview of Mechanism

LAP WS

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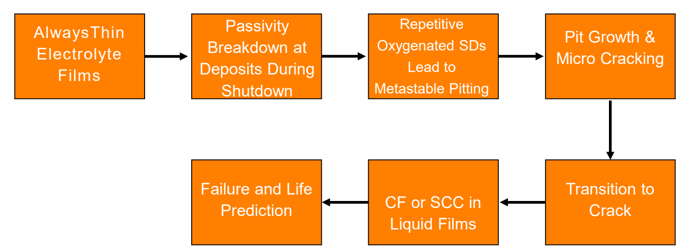
Processes During Corrosion Cracking in PTZ



LAP WS

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Deposit Formation in Turbines

- Precipitation from superheated steam
- Evaporation of moisture (liquid films)
- Deposition/impingement of metal oxides
- Deposition/impingement of salt crystals
- Adsorption of impurities
- Depends on materials and surface finish
- Carryover and Drum Level Control

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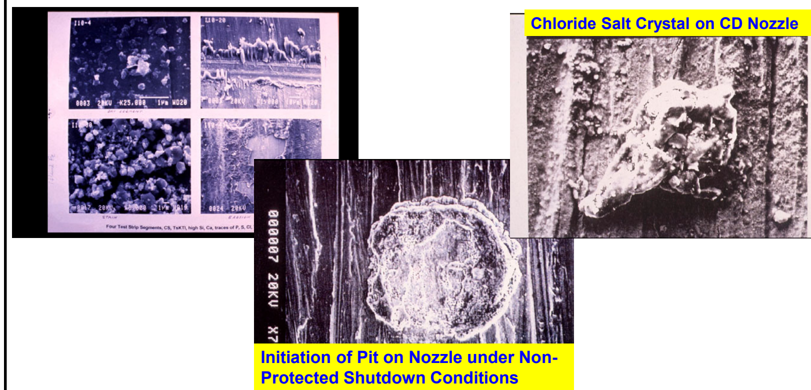
Salt Crystals Deposit even on units with Best Steam Purity



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Regimes of PTZ Failure

Initiation

- Localized corrosion in the form of pitting requires the presence of an (aggressive) species **(deposit)** for inducing passivity breakdown during **Non-protected shutdown.** (ECP and concentration of chloride ion)
- Metastable (passivity breakdown) and stable pits.
- **Repetitive non-protected shutdowns** allow pits to grow to critical size in order to nucleate micro-cracks.
- May be other materials defects. Surface preparation.
- Often long periods of time spent in this stage.
- Damage hard to detect in this stage and often missed during NDE/inspections.

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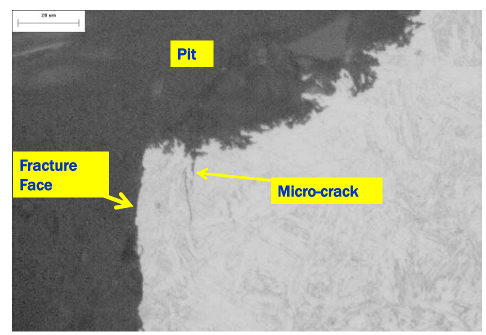
Example of Transition from Pit to Micro-Crack on L-1 Blade that failed due to CF



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Example: Mobile Dehumidification System Connected to Steam Extraction Line

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Overall Solution to PTZ Damage: Keep the Blades and Disks Dry During Shutdown

- Only if the blade and disk surfaces are absolutely dry during shutdown (and the chloride level and/or ECP is reduced to acceptable levels) can the development of corrosion damage upon shutdown be inhibited and hence the nucleation of corrosion fatigue and stress corrosion cracks and subsequent failure be prevented.
- Options include to keep the blades dry after more than three days shutdown with dehumidified air, or use a FFS to provide a hydrophobic film on the PTZ surfaces

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RCCS which Lead to PTZ Deposits and Failures

All have been observed in hundreds of case studies but there are IAPWS TGD to avoid*

IAPWS TGD: Contaminants; Instrumentation; Carryover; Shutdown Protection; Status Quo; Steam Purity

- Repetitive contamination above Action Level *
- Contaminant ingress above shutdown limit *
- Continued attemperation during contamination *
- Lack of, reduced level of, on-line instrumentation** *
  - No steam monitoring is most common
- No knowledge of carryover from drums* *
- No LP steam turbine shutdown protection with DHA (and/or FFS) *
- High level of air in-leakage* *
- No challenge of status quo* *
  - Operating with original chemistry
  - Changing chemistry, but keep part of the old chemistry
  - Changing shutdown limit
  - Changing from 2x1 to 1x1

IAPWS Instrumentation TGD02-09, September 2024 www.IAPWS.org

IAPWS Carryover TGD01-08, September 2008 www.IAPWS.org

New RCCS & Benchmarking TGD Planned for 2026

End of Part 1. Over to Bobby

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A few concluding remarks from IAPWS, Bobby and Barry:

- Pits, Deposits, Early Condensate, and Liquid Films are major processes in PTZ of Steam Turbine which lead to SCC and CF
- Each is fully understood and influenced by the cycle chemistry
- Multiple Repeat Cycle Chemistry Situations (RCCS) are always identified when failure/damage occurs
- The IAPWS TGD address each RCCS
- The IAPWS Guidance represents the International Standard for Steam Purity and addresses the Major PTZ Chemistry aspects:
  - Guidance for all types of turbines and IAPWS Chemistries
  - How to address contaminants, CO_2, organics, etc.
  - Shutdown protection.

Discussion by Users

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IAPWS TGD5-13

The International Association for the Properties of Water and Steam

London, United Kingdom
September 2013

Technical Guidance Document: Steam Purity for Turbine Operation

President:
Professor Tamara Petrova
Moscow Power Engineering Institute
Moscow, Russia

Executive Secretary:
Dr. R. B. Dooley
Structural Integrity Associates
Email: bdooley@structint.com

This document contains 37 pages, including this cover page.

This technical guidance document has been authorized by the International Association for the Properties of Water and Steam (IAPWS) at its meeting in London, UK, 1–6 September 2013, for issue by its Secretariat. The members of IAPWS are: Britain and Ireland, Canada, the Czech Republic, Germany, Japan, Russia, Scandinavia (Denmark, Finland, Norway and Sweden), and the United States of America, and Associate Members Argentina and Brazil, Australia, France, Greece, Italy, New Zealand and Switzerland. The document represents the accumulated experience of the IAPWS Power Cycle Chemistry (PCC) Working Group with representation from 17 countries.

This technical guidance document considers steam turbines from power plants using fossil, combined cycle, nuclear, alternative and geothermal energy, including turbines in industrial applications. It is emphasized that this is an IAPWS technical guidance document and that, depending on local requirements, the normal or target values will need to be customized for each case, depending on the actual conditions of operation, the type of generation and use of the steam, and the power cycle chemistry.

Further information about this technical guidance document and other documents issued by IAPWS can be obtained from the Executive Secretary of IAPWS or from http://www.iapws.org.

This document can be downloaded (for free) at:

www.iapws.org

Table of content of TGD5-13

Part 3 has just been covered by Barry
the following will expand parts 4, 5 and 6

4 Requirements to Limit the Effects of Poor Steam Chemistry

- 4.1 Steam Purity Parameters
  - ☐ 4.1.1 Impurities
  - ☐ 4.1.2 Conditioning Agents
- 4.2 Monitoring Instrumentation
- ☐ 4.3 Layup
- ☐ 4.4 Mitigating Consequences of Sub-optimum Steam Chemistry

4 Requirements to Limit the Effects of Poor Steam Chemistry
4.1 Steam Purity Parameters

4.1.1 Impurities (1)

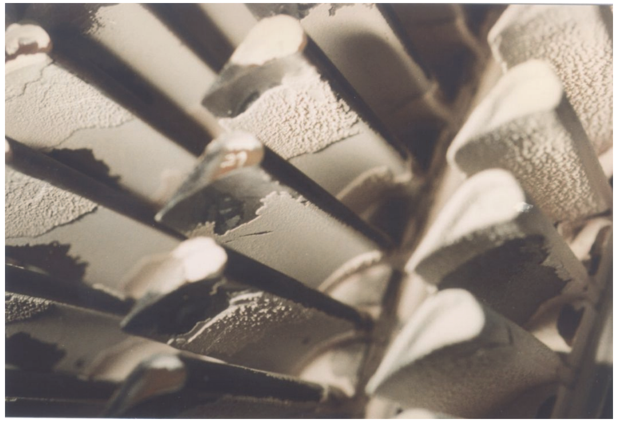
Conductivity after cation exchange (CACE)
Degassed CACE
→ general indication of impurities

Carbon dioxide
→ harmless in the steam turbine
problem in heat exchangers

Sodium
Chloride and Sulfate
→ corrosive deposits
deposits may also obstruct steam flow

Silica
Copper
Iron
Aluminum
→ deposits may obstrucht steam flow
and cause overheating in the boiler

Organic matter
→ may be corrosive



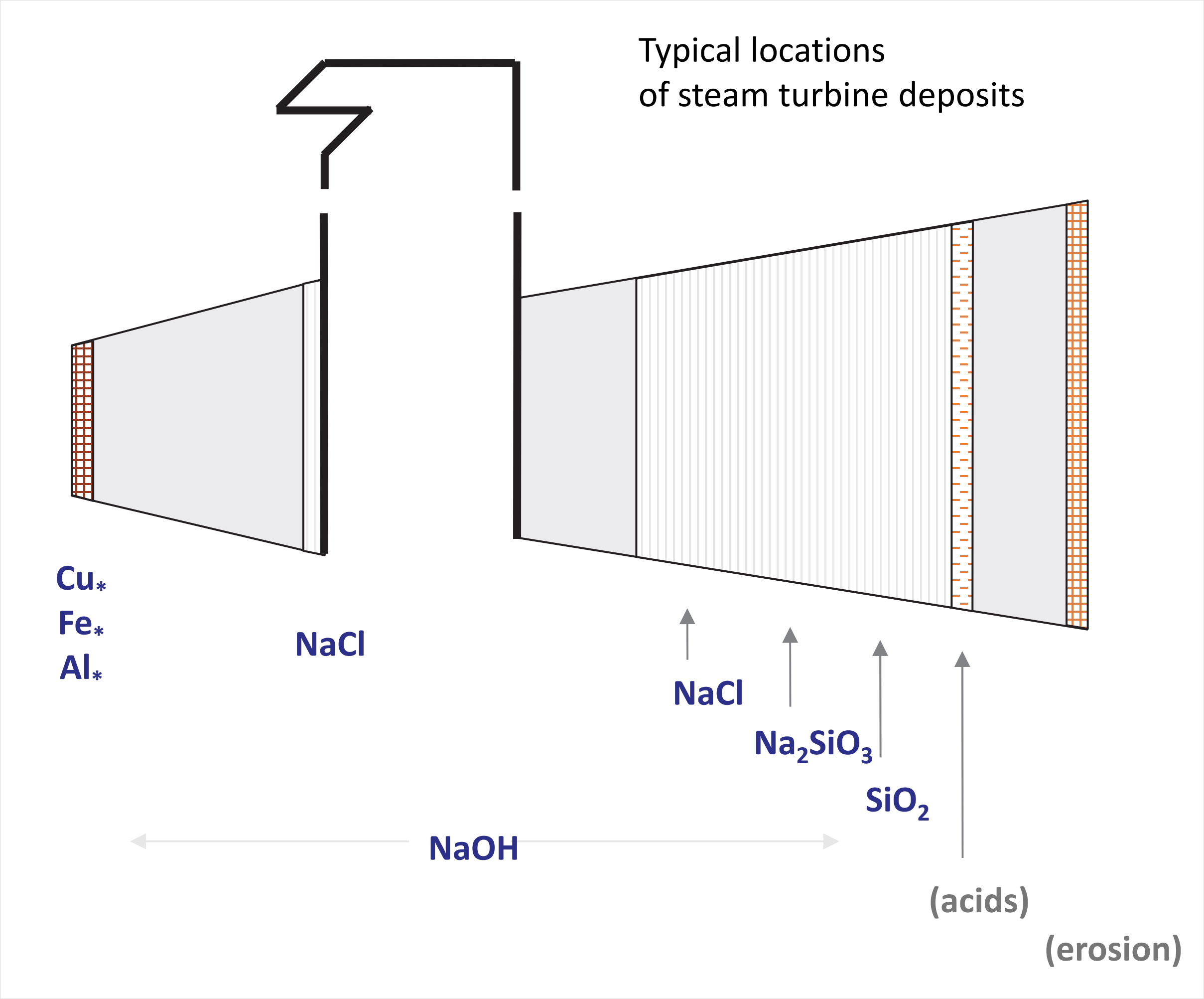
left: phosphate deposits on the stem
of a turbine check valve -> safety issue

center: overheating of a superheater tube
due to salt deposits -> tube failure

right: Silica deposits on turbine blades
-> degradation of flow and Turbine output

4 Requirements to Limit the Effects of Poor Steam Chemistry
4.1 Steam Purity Parameters

4.1.1 Impurities (2)



NaOH

- either deposits
- or concentraded liquid films up to high temperatures

-> stress corrosion cracking of sensitive materials

- austenites
- non-stress relieved weldings
- Stellite
- high-strength steels
- stressed ferritic steels (mechanical or internal stresses)

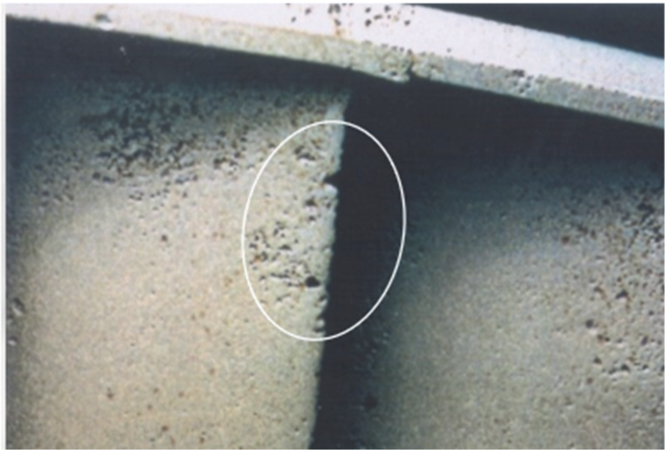
4 Requirements to Limit the Effects of Poor Steam Chemistry
4.1 Steam Purity Parameters

4.1.2 Conditioning Agents

Ammonia	Good alkalizing properties, but stays mainly in steam phase at elevated temperature -> moderate alkalization in the PTZ
Amines	Better partition into the liquid phase, but generally lower alkalization strength -> better alkalization in the PTZ organic amines: acidic decomposition products, usually compensated by the alkalization but acidic products disturb CACE measurements, potentially hiding other contaminants
FFS (Film forming substances)	additionally hydrophobic surface effects -> better corrosion protection acidic decomposition products, depending on product and operating parameters
Reducing Agents	if (!) used, organic substances will produce acidic decomposition products, without delivering additional alkalizing products to compensate the acids

4 Requirements to Limit the Effects of Poor Steam Chemistry
4.3 Layup

This is a reminder of the importance of proper layup as has been outlined by Barry



4 Requirements to Limit the Effects of Poor Steam Chemistry
4.4 Mitigating Consequences of Sub-optimum Steam Chemistry

First commissioning

Unforeseeable situations

Impurity deposits in the turbine, insoluble in water — specific cleaning methods, e.g. sanblasting

Impurity deposits in the turbine, soluble in water — washing with water or wet steam

Impurity deposits in the turbine valves — clean valves; check valves function daily

Acid conditions

Degradation of the water / steam separation

5 Table of Chemistry Limits

5.1 Table of Steam Purity Limits

- ☐ 5.1.1 Condensing Turbines with Superheated Steam
- ☐ 5.1.2 Condensing Turbines with Saturated Steam

5.2 Limits for Normal Operation

- ☐ 5.3 Development of Limits for Startup

5.4 Development of Action Levels

5.5 Development of Shutdown Limits

5 Table of Chemistry Limits
5.1 Table of Steam Purity Limits

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.

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.

5 Table of Chemistry Limits
5.3 Development of Limits for Startup

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

These normal operation values can usually not be attained during plant startup

Example of a customized specification for startup

Na µg/kg	CACE * µS/cm	Restrictions
> 20	> 2	Do not pass steam to turbine
10 … 20	1 … 2	- Steam production < 40% nominal - Max 30 min per startup
n … 10	n … 1	Max 8 hours per startup

Table 3. Na and CACE during startup; *n* = normal operation value.

* maximum permissible allowance for carbon dioxide (on-line instrument readings).

Further instructions on customizing are given in IAPWS/PCC White Paper

“Corrosion Product Sampling, Monitoring and Analysis for Flexible and Fast Starting Plants”

www.iapws.org/working-groups/PCC

5 Table of Chemistry Limits

5.3 Development of Limits for Startup

POWER CYCLE CHEMISTRY WORKING GROUP (PCC WG)

INTERNATIONAL ASSOCIATION FOR THE PROPERTIES OF WATER & STEAM

The International Association for the Properties of Water and Steam (IAPWS) Power Cycle Chemistry (PCC) Working Group

White Paper

Corrosion Product Sampling, Monitoring and Analysis for Flexible and Fast Starting Plants

Revision 3.1, January 2025
PCC W P 24-001

Please cite as: International Association for the Properties of Water and Steam, Power Cycle Chemistry Working Group *White Paper: Corrosion Product Sampling, Monitoring and Analysis for Flexible and Fast Starting Plants, Revision 3.1, January 2025, PCC W P 24-001*

Key Power Cycle Chemistry Work Group Contacts for this document are
1. Barry Dooley, Task Group Chair, bdooley@structint.com
2. David Addison, Current PCC Chair at the time of release, david.addison@thermalchemistry.com

This White Paper has been released by the International Association for the Properties of Water and Steam (IAPWS) Power Cycle Chemistry (PCC) Working Group. An IAPWS PCC White Paper is intended to be a preliminary technical document collating knowledge on a particular subject to provide a basis for the potential future development of a related Technical Guidance Document. They are not formal IAPWS outputs as such.

This document can be downloaded (for free) from:

www.iapws.org/working-groups/PCC

6 Road Map Approach to Customize Steam Purity Limits to Plants with Specific Features

- ☐ 6.1 Turbines for Cycling or Peaking Operation
- 6.2 Turbines with Extended Periods of Shutdown
- ☐ 6.3 Backpressure Turbines
- ☐ 6.4 Turbines for Industry and Process Supply
- 6.5 Turbines with Solar and Biomass Steam Generating Systems
- 6.6 Turbines with Geothermal Steam
- ☐ 6.7 Turbines with Steam Generated in Nuclear Power Plants
- 6.8 Ultrasupercritical Turbines with Steam Temperatures >600 °C
- 6.9 Turbines in Plants with Boilers using Phosphate Treatment
- ☐ 6.10 Turbines with Steam containing Elevated Levels of Carbon Dioxide
- ☐ 6.11 Turbines with Steam containing Organic Decomposition Products
- 6.12 Turbines with Steam containing Elevated Levels of Silica
- 6.13 Turbines in Power Cycles containing Major Components with Copper or Aluminum

although steam generation may be very different, the requirements of the turbine are essentially the same

6 Road Map Approach to Customize Steam Purity Limits to Plants with Specific Features

6.1 Turbines for Cycling or Peaking Operation

Load changes: should not result in major deviations from normal. If not so, it indicates inadequate conditions that require expert analysis

Startups: follow customization as outlined in Section 5.3, and in the PCC White Paper

Shutdown: special care required to avoid corrosive conditions, e.g. avoid hood spray

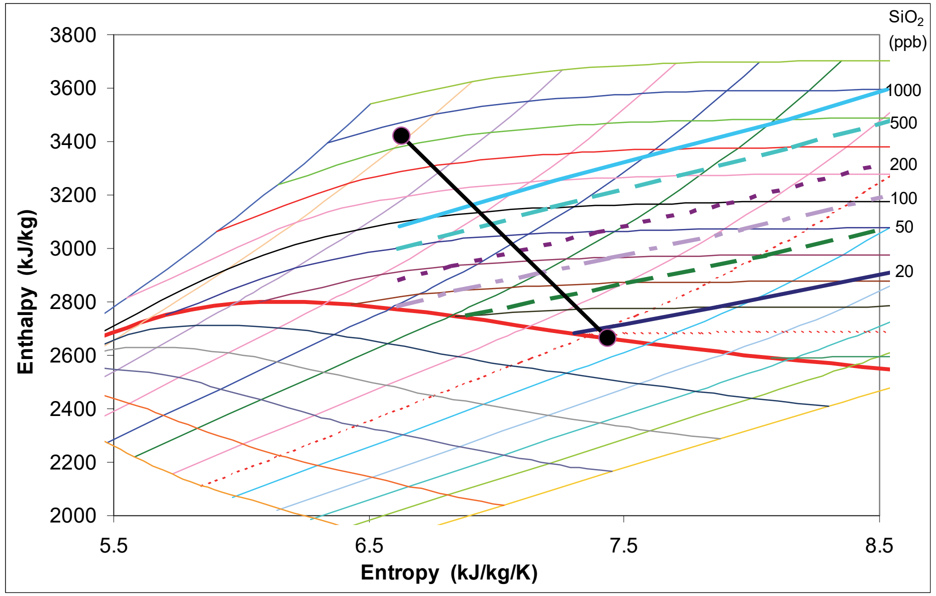
Periods of layup: keep condenser vacuum or keep turbine temperature high, or apply dry air storage

6 Road Map Approach to Customize Steam Purity Limits to Plants with Specific Features

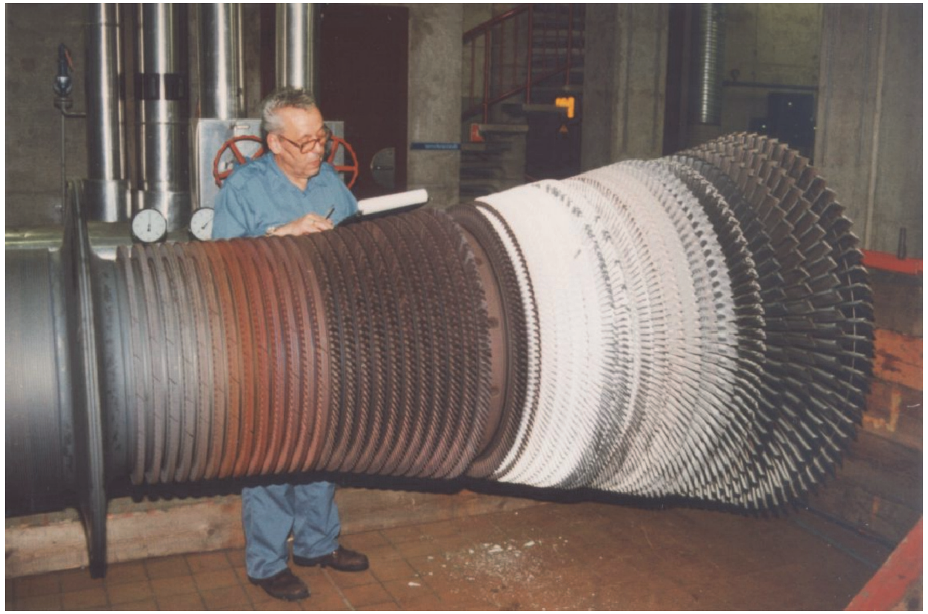
6.3 Backpressure Turbines

Non-condensing backpressure turbines:

- no Phase Transition Zone for the usual impurities
- but decrease of solubility of solid impurities



Solubility of Silica in Steam and expansion curve of backpressure turbine



Backpressure Turbine 48 MW, 106 bar / 520°C with Silica deposits

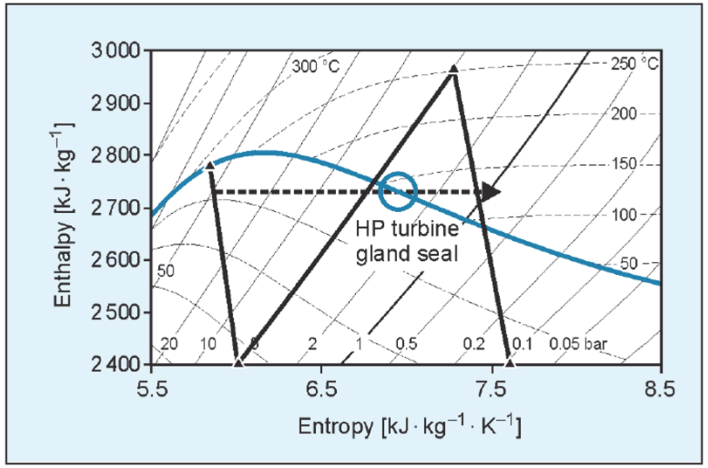
6.4 Turbines for Industry and Process Supply

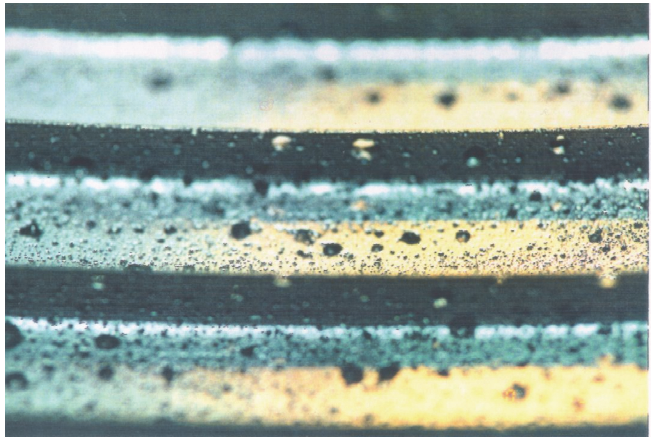
Although steam purity may be compromised by the industrial process (e.g. by return condensates, use of NaOH), the requirements of the turbine remain essentially the same. However, compromises may be required

- follow guidance given for turbines with cycling operation
- take preventive or mitigating action:
  - exercise turbine trip and throttle valves at least once a week
  - check regularly turbine stage pressures
  - make turbine regular turbine inspections
  - make reguler deposit analysis to identify main risk sources
  - if there is deposit buidup, wash turbine and turbine inlet valves, or consider off-line deposit removal method (e.g. foam cleaning, sand blasting)
  - the importance of proper layup must be taken into account

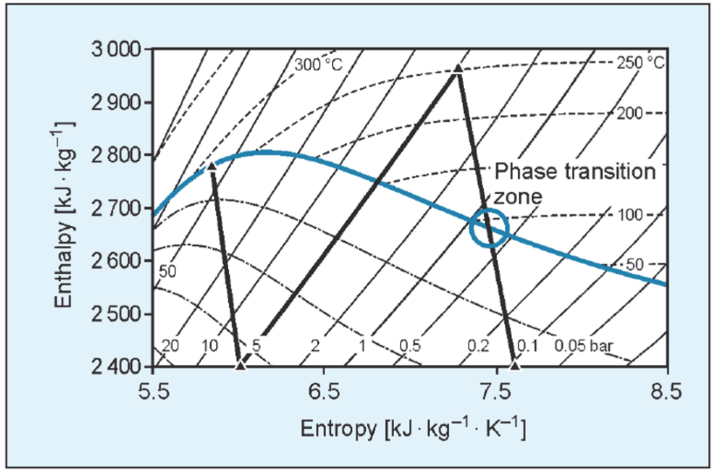
6.7 Turbines with Steam Generated in Nuclear Power Plants

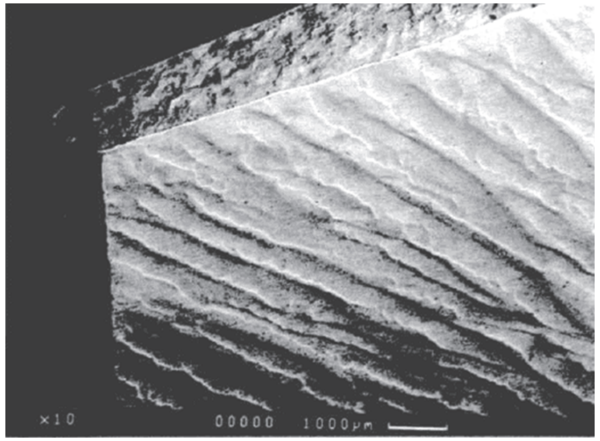
Although steam generation is very different, the requirements of the turbine are essentially the same
good steam generator (reactor) water chemistry is NOT sufficient





Boiling Water Reactor
Pitting corrosion in the gland seal of the HP turbine
(12% Cr steel)





Boiling Water Reactor
Flow Accelerated Corrosion on LP statonary blades
(low-alloy steel)

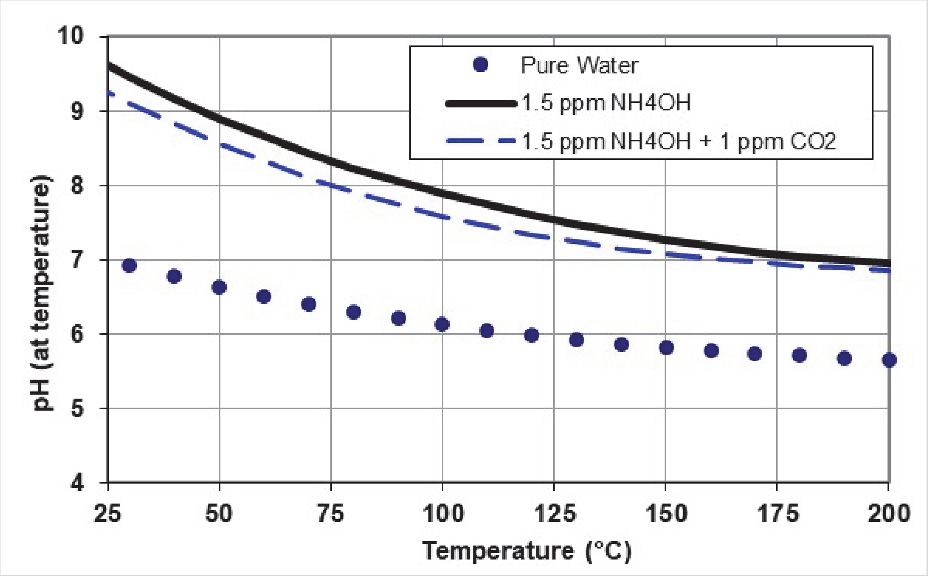
6.10 Turbines with Steam containing Elevated Levels of Carbon Dioxide

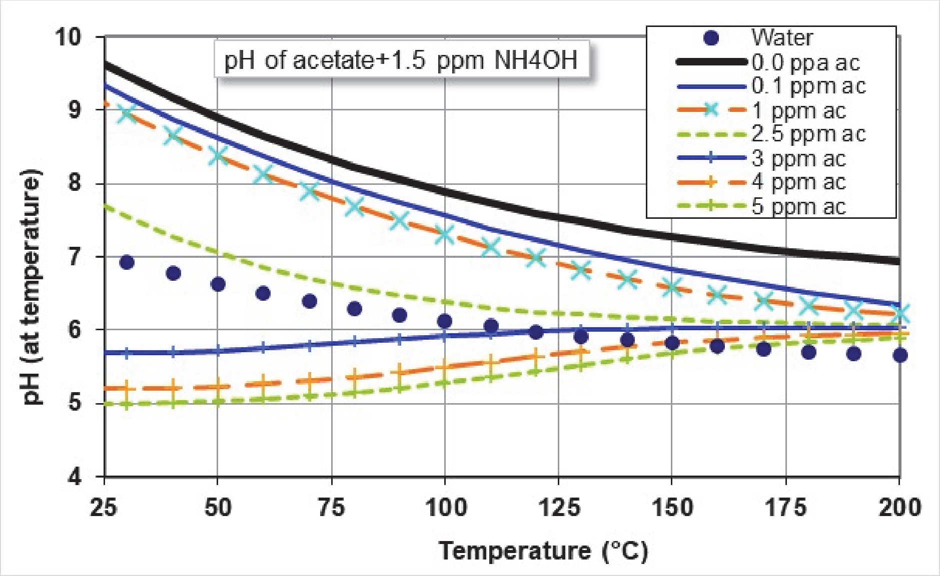
At temperatures found in the PTZ, carbon dioxide has a high volatility and a weak dissociation.
Therefore, additional allowance for carbon dioxide can be given to the steam purity limits such

- restricted such that in no instance may CACE* exceed 2 µS/cm.
- if the alkalization of steam is low (circa pH<8.5), no additional allowance for carbon dioxide shall be given.

=> problem: increased CACE may hide other, detrimental acidic impurities

* CACE = conductivity after cation exchanger





6.11 Turbines with Steam containing Organic Decomposition Products

FAC on the turbine case at the PTZ
non-alloyed cast iron, steam moisture <2%, CACE 0.2-0.7 µS/cm
caused by decomposition of organics in peaty water

Organic decomposition products are mostly acidic
main effect is on pH in the liquid phase, especially in the PTZ

- Flow Accelerated Corrosion (FAC)
- Corrosion fatigue (CF)

- *amines used for feedwater treatment – oK, when amine neutralizes organic decomposition product in the PTZ (depends on amine) -> have to know which products!*
- *organic oxygen scavengers: no cation that can compensate effect of acid in PTZ*
- *natural organic matter no cation that can compensate effect of acid in PTZ*
- *impairment of monitoring (increase of CACE),*
  additional chemical analyses required to ensure that the elevation is not due to Cl or SO_4

A few concluding remarks from IAPWS, Bobby and Barry:

- Pits, Deposits, Early Condensate, and Liquid Films are major processes in PTZ of Steam Turbine which lead to SCC and CF
- Each is fully understood and influenced by the cycle chemistry
- Multiple Repeat Cycle Chemistry Situations (RCCS) are always identified when failure/damage occurs
- The IAPWS TGD address each RCCS
- The IAPWS Guidance represents the International Standard for Steam Purity and addresses the Major PTZ Chemistry aspects:
  - Guidance for all types of turbines and IAPWS Chemistries
  - How to address contaminants, CO_2, organics, etc.
  - Shutdown protection.

Discussion by Users

IAPWS