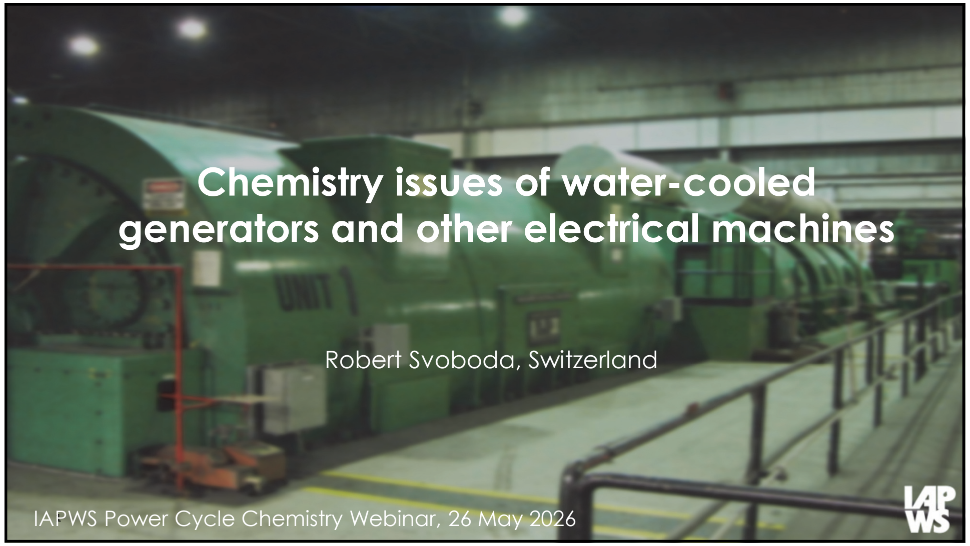

Chemistry issues of water-cooled generators and other electrical machines

Robert Svoboda, Switzerland

IAPWS Power Cycle Chemistry Webinar, 26 May 2026

1

... generators and other electrical machines ??

Water-cooled components in:

- Particle accelerators (-> magnets)
  - research
  - medicine
- Rectifiers
- Power transmission equipment
- High power radar equipment (-> magnetrons)

2

Reference Documents:

The International Association for the Properties of Water and Steam

Banff, Canada
October 2019

Technical Guidance Document:
Chemistry Management in Generator Water Cooling
during Operation and Shutdown

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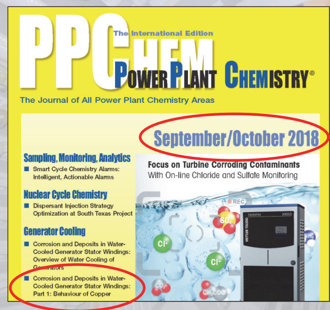
download at:
www.iapws.org

3

Reference Documents

More details for this presentation:
in Sep/Oct 2018 issue of PPChem

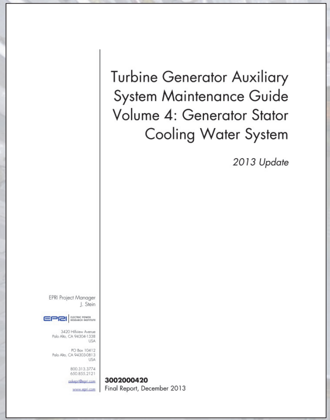


Series of papers in PPChem journal:
Corrosion of Water-cooled Generator Stator Windings:
- Overview of Water Cooling
- Part 1: Behaviour of Copper
- Part 2: Detection of Flow Restrictions
- Part 3: Removal of Flow Restrictions
- Part 4: Operating Experience with Flow Restrictions

These papers were published in PPChem 2018 and 2019
No significant new aspects have come up since then
Reprints are available from PPChem, from the author and at ResearchGate
www.ppchem.com www.researchgate.net

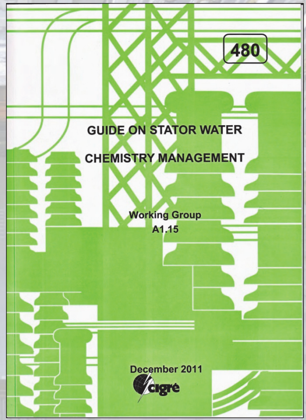
4

Reference Documents


Turbine Generator Auxiliary System Maintenance Guide Volume 4: Generator Stator Cooling Water System

2013 Update

3002000420
Final Report, December 2013


480

GUIDE ON STATOR WATER CHEMISTRY MANAGEMENT

Working Group A1.15

December 2011

cigre

Usage of stator water cooling

History

1956 AEI (GEC) / England, 30 MW
1957 China, 10-25 MW, stator and rotor
1960 Commercial use, usually for >400 MW

Distribution (2018)

Part of the world	Stators	Rotors
World ex Russia & China	2000	80
Russia	800	60
China	>1200	many

Numbers are approximate
Numbers for China are estimated

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Generator cooling: chemistry related problem areas

General
- Retaining Ring Cracking

Air cooling
- Atmospheric corrosion and plugging

Water cooling
- Corrosion and plugging of hollow conductors
- Conductive deposits in insulation hoses
- Clip-to-strand leakage
- Plugging of strainers and filters in the cooling water system
- Corrosion of coolers and cooling water inleakage

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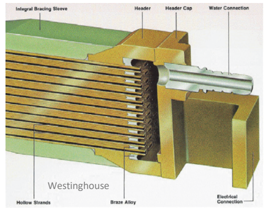
Generator cooling: chemistry related problem areas

General
- Retaining Ring Cracking

Air cooling
- Atmospheric corrosion and plugging

Water cooling
- Corrosion and plugging of hollow conductors
- Conductive deposits in insulation hoses — mostly with DC, e.g.rotor
- Clip-to-strand leakage — OEM specific
- Plugging of strainers and filters — OEM specific
- Corrosion of coolers and cooling water inleakage



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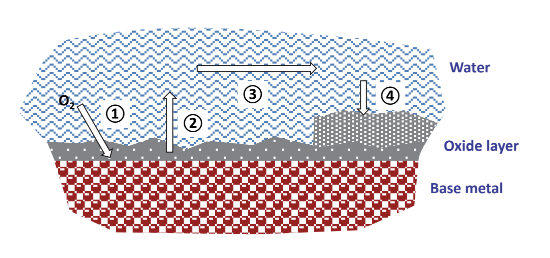
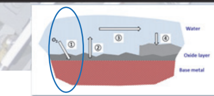
Mechanism for Hollow Conductor Plugging



① Oxidation of the copper surface
② Release of the oxidized copper (particle or ion)
③ Migration of the released copper
④ Re-deposition (precipitation) of the migrating copper

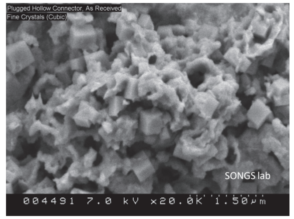
① Oxidation of the copper surface



$2Cu + O_2 \rightarrow 2CuO$
$4Cu + O_2 \rightarrow 2Cu_2O$

Found in generator deposits
- Always a mix of Cu_2O and CuO
- Often with fraction of metallic Cu

Proportion of Cu_2O / CuO
- High oxygen chemistry: more CuO
- Low-oxygen chemistry: more Cu_2O



Cu_2O / CuO deposits in a plugged hollow conductor

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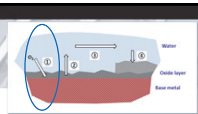
① Oxidation of the copper surface



In low-oxygen generator cooling systems
All oxygen is consumed by the coil

→ Every gram of oxygen entering into the system
- makes 9 grams of Cu_2O — $4Cu^{+} + O_2 \rightarrow 2Cu_2O$
- or 4 grams of CuO — $2Cu^{++} + O_2 \rightarrow 2CuO$

.... independent of water chemistry

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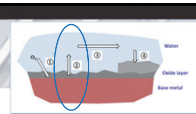
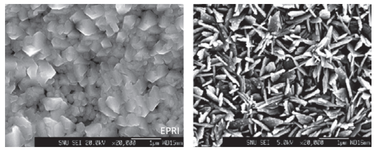
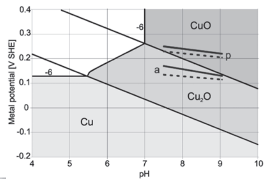
② Release of the Oxidized Copper



- Particles or colloid (Cu-oxides or Cu)
  - instability of the oxide structure
    e.g. change from Cu_2O to CuO
    - air ingress in low-oxygen chemistry $2Cu_2O+O_2 \rightarrow 2CuO$
    - pH change
  - partial dissolution of the oxide layer etc.
  - Electrochemical Potential (ECP)
- Dissolved copper ion (Cu^{++} and Cu^{+})



Copper oxides under different water chemistries



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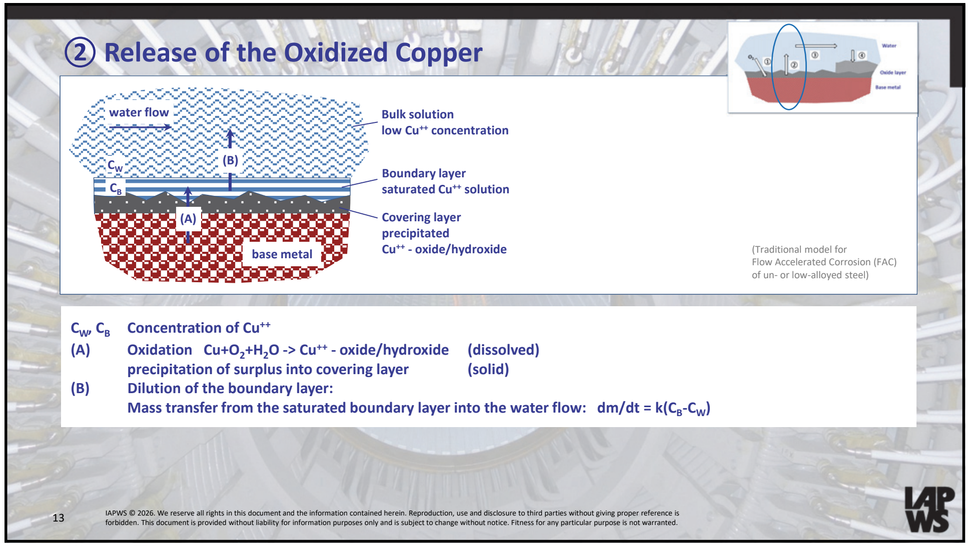
② Release of the Oxidized Copper
water flow
(B)
C_W
C_B
(A)
base metal
Bulk solution
low Cu^{++} concentration
Boundary layer
saturated Cu^{++} solution
Covering layer
precipitated
Cu^{++} - oxide/hydroxide
(Traditional model for
Flow Accelerated Corrosion (FAC)
of un- or low-alloyed steel)
C_W, C_B Concentration of Cu^{++}
(A) Oxidation $Cu+O_2+H_2O$ -> Cu^{++} - oxide/hydroxide (dissolved)
precipitation of surplus into covering layer (solid)
(B) Dilution of the boundary layer:
Mass transfer from the saturated boundary layer into the water flow: $dm/dt = k(C_B-C_W)$
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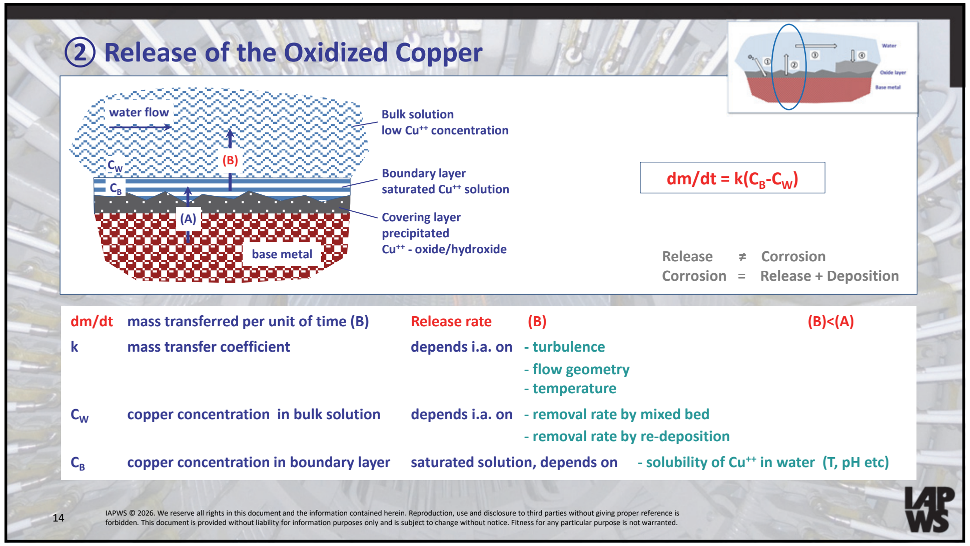
② Release of the Oxidized Copper
water flow
(B)
C_W
C_B
(A)
base metal
Bulk solution
low Cu^{++} concentration
Boundary layer
saturated Cu^{++} solution
Covering layer
precipitated
Cu^{++} - oxide/hydroxide
$dm/dt = k(C_B-C_W)$
Release ≠ Corrosion
Corrosion = Release + Deposition
dm/dt mass transferred per unit of time (B) Release rate (B) (B)<(A)
k mass transfer coefficient depends i.a. on - turbulence
- flow geometry
- temperature
C_W copper concentration in bulk solution depends i.a. on - removal rate by mixed bed
- removal rate by re-deposition
C_B copper concentration in boundary layer saturated solution, depends on - solubility of Cu^{++} in water (T, pH etc)
14
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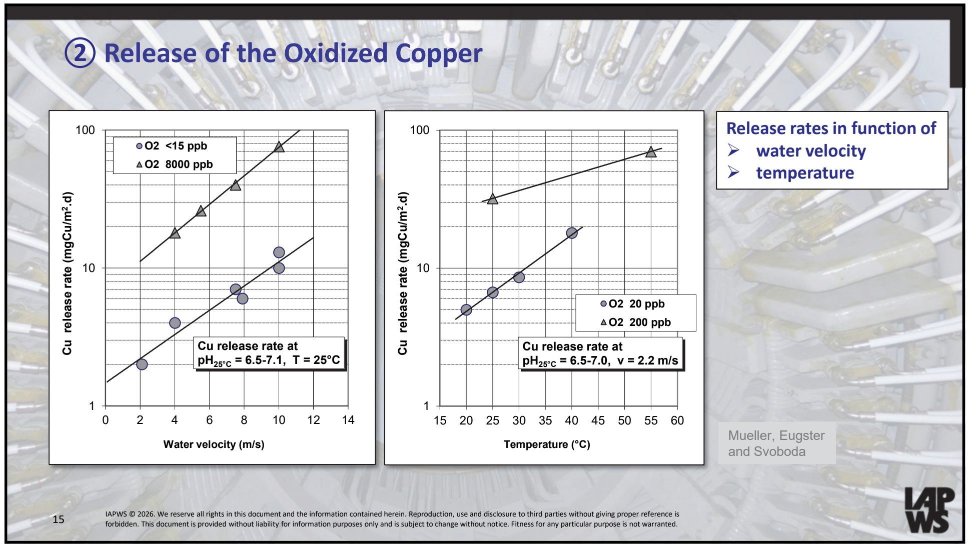
② Release of the Oxidized Copper
O2 <15 ppb
O2 8000 ppb
Cu release rate at
$pH_{25°C}$ = 6.5-7.1, T = 25°C
Cu release rate (mgCu/m².d)
Water velocity (m/s)
O2 20 ppb
O2 200 ppb
Cu release rate at
$pH_{25°C}$ = 6.5-7.0, v = 2.2 m/s
Temperature (°C)
Release rates in function of
➢ water velocity
➢ temperature
Mueller, Eugster
and Svoboda
15
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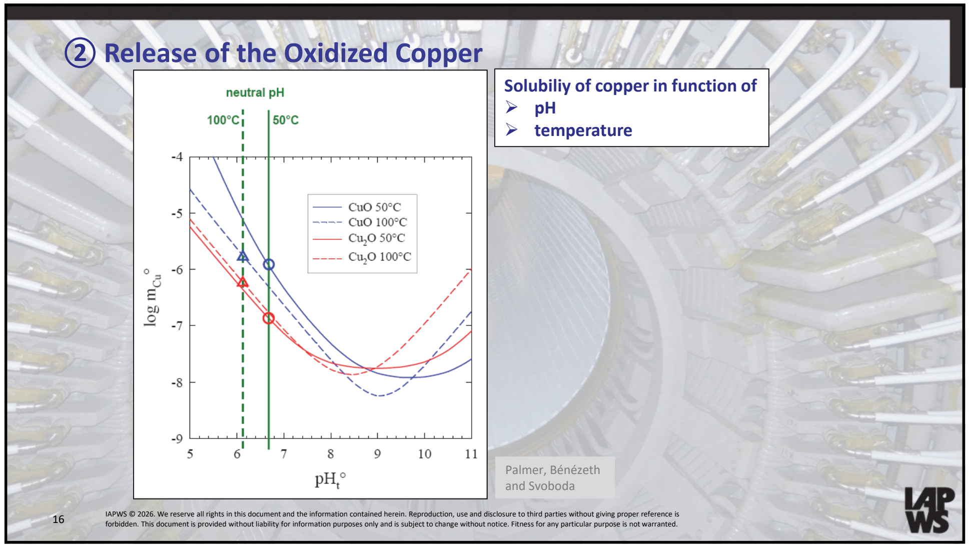
② Release of the Oxidized Copper
neutral pH
100°C
50°C
CuO 50°C
CuO 100°C
Cu_2O 50°C
Cu_2O 100°C
log m_{Cu}
$pH_t°$
Solubiliy of copper in function of
➢ pH
➢ temperature
Palmer, Bénézeth
and Svoboda
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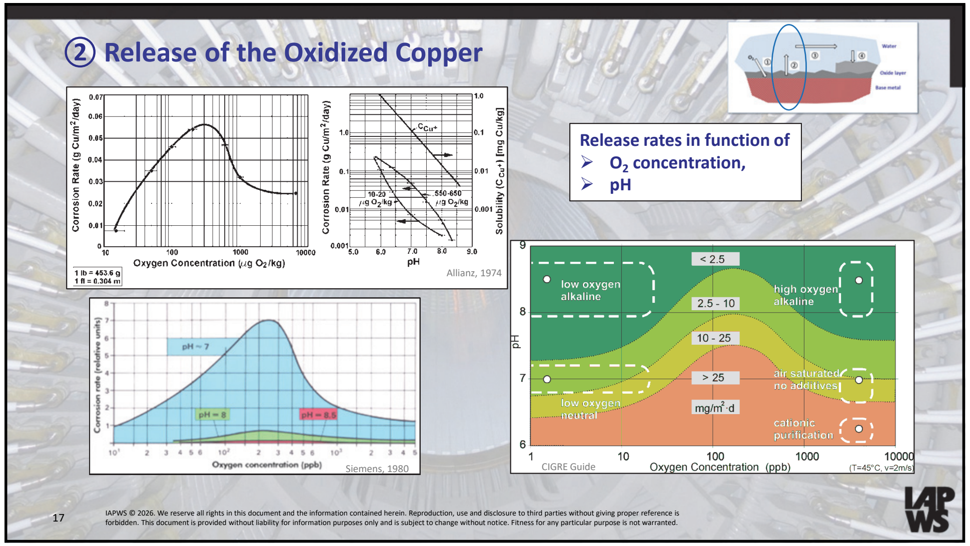
② Release of the Oxidized Copper
Release rates in function of
O₂ concentration,
pH
Corrosion Rate (g Cu/m²/day)
Oxygen Concentration (µg O₂/kg)
1 lb = 453.6 g
1 ft = 0.304 m
Solubility (C_Cu+) [mg Cu/kg]
pH
Allianz, 1974
pH ~ 7
pH = 8
pH = 8.5
Oxygen concentration (ppb)
Siemens, 1980
< 2.5
2.5 - 10
10 - 25
> 25
mg/m²·d
low oxygen alkaline
high oxygen alkaline
air saturated no additives
low oxygen neutral
cationic purification
Oxygen Concentration (ppb)
CIGRE Guide
(T=45°C, v=2m/s)
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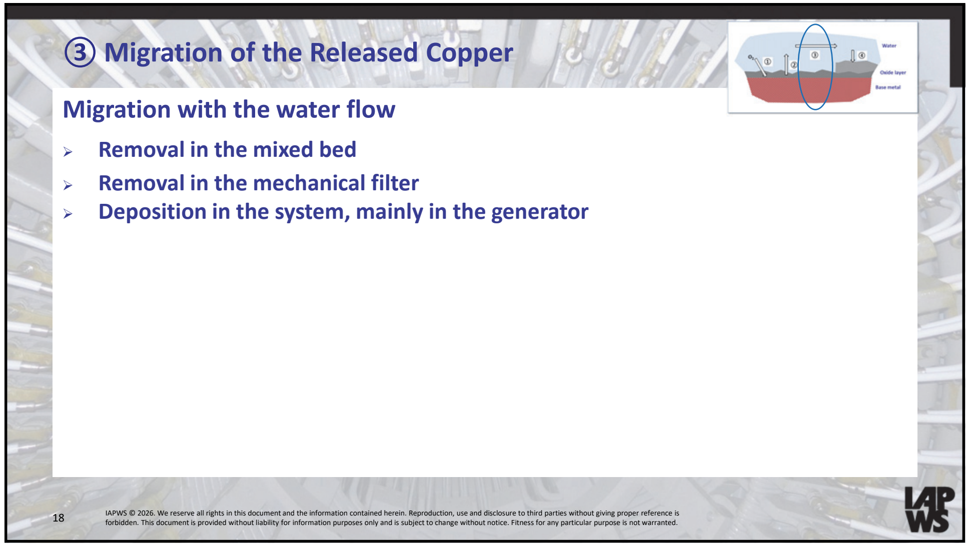
③ Migration of the Released Copper
Migration with the water flow
Removal in the mixed bed
Removal in the mechanical filter
Deposition in the system, mainly in the generator
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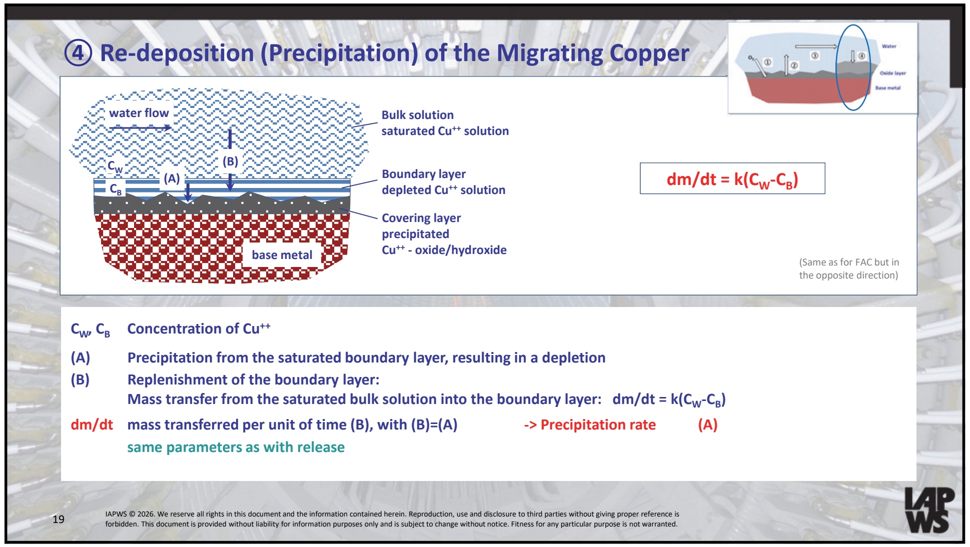
④ Re-deposition (Precipitation) of the Migrating Copper
water flow
Bulk solution saturated Cu⁺⁺ solution
Boundary layer depleted Cu⁺⁺ solution
Covering layer precipitated Cu⁺⁺ - oxide/hydroxide
base metal
dm/dt = k(C_W-C_B)
(Same as for FAC but in the opposite direction)
C_W, C_B Concentration of Cu⁺⁺
(A) Precipitation from the saturated boundary layer, resulting in a depletion
(B) Replenishment of the boundary layer:
Mass transfer from the saturated bulk solution into the boundary layer: dm/dt = k(C_W-C_B)
dm/dt mass transferred per unit of time (B), with (B)=(A) -> Precipitation rate (A)
same parameters as with release
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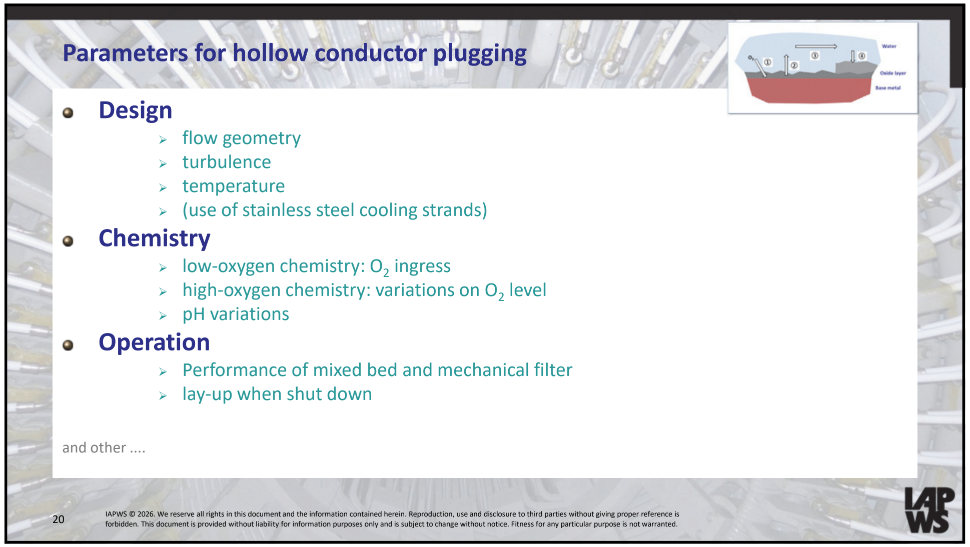
Parameters for hollow conductor plugging
Design
flow geometry
turbulence
temperature
(use of stainless steel cooling strands)
Chemistry
low-oxygen chemistry: O₂ ingress
high-oxygen chemistry: variations on O₂ level
pH variations
Operation
Performance of mixed bed and mechanical filter
lay-up when shut down
and other ....
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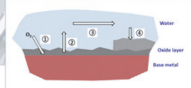
Parameters for hollow conductor plugging



- **Design**
  - flow geometry
  - turbulence
  - temperature
  - (use of stainless steel cooling strands)
- **Chemistry**
  - low-oxygen chemistry: O_2 ingress
  - high-oxygen chemistry: variations on O_2 level
  - pH variations
- **Operation**
  - Performance of mixed bed and mechanical filter
  - lay-up when shut down

and other ....

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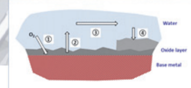
21

Strategies to avoid Hollow Conductor Plugging



- **Water chemistry**

Type of Water Treatment	Keep Oxidation Low	Keep Release Rate Low	Direct Transport into Ion-Exchanger	Keep Re-deposition Low
Low-oxygen / neutral	x			
Low-oxygen / alkaline	x	x		
High-oxygen / neutral		x	x	
High-oxygen / alkaline		x		
Cationic purification *			x	x

x target parameter for the respective water treatment
* treatment for temporary use only

* temporarily slightly acidic with CO_2 from air
use of cation resin instead of mixed bed

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Usage of stator water chemistry

Distribution (2018)

Part of the world	Stators	Rotors	Stator water chemistry		
			high oxygen	low oxygen	hereof alkaline
World ex Russia & China	2000	80	1100	900	260
Russia	800	60	0	800	0
China *	>1200	many	?	most	?

Numbers are approximate, * only estimates for China

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Water chemistry specifications

- **High-oxygen chemistry**

Parameter	Normal operating value	Short term action level	
Conductivity (25°C), µS/cm	≤ 0.2	> 10 * > 0.15	neutral water treatment “start troubleshooting”
	≤ 2	> 10	alkaline water treatment **
Oxygen, µg/kg (ppb)	≥ 2000	< 1000	
ECP ***, mV SHE	> 315	< 305	

* Generic value for generator shutdown, may differ with OEM and specific generator
** Alkaline water treatment means pH 8.5–9.0
*** Electrochemical potential (ECP): tentative specification.

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Water chemistry specifications

- **Low-oxygen chemistry**

Parameter	Normal operating value	Short term action level	
Conductivity (25°C), µS/cm	≤ 0.2	> 10 * > 0.15	neutral water treatment "start troubleshooting"
	≤ 2	> 10	alkaline water treatment **
Oxygen, µg/kg(ppb)	≤ 20	> 50	"as low as possible"
		> 10 above normal	"start troubleshooting"
ECP ***, mV SHE	< 223	> 266	

* Generic value for generator shutdown, may differ with OEM and specific generator
** Alkaline water treatment means pH 8.5–9.0
*** Electrochemical potential (ECP): tentative specification.

Water chemistry specifications

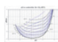
- **Stainless steel hollow conductors**

Parameter	During operation	During shutdown	
Conductivity (25°C), µS/cm	< 0.3	< 0.3 *	* if stator is left filled, or before draining
Oxygen, µg/kg (ppb)	-	-	no requirement
Copper, µg/kg (ppb)	< 10	-	
Iron, µg/kg (ppb)	< 10	-	

Water chemistry specifications

Conductivity limit (1):

- **neutral water treatment**
  - simple to achieve in a normal operating system
  - limit pH excursions -> 0.2 µS/cm
    and take action at -> 0.15 µS/cm

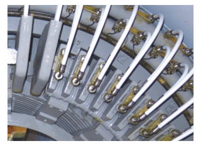


- **alkaline water treatment**
  - allowance for NaOH: e.g. 2 µS/cm
- **stainless steel hollow conductors**
  - indirect limit for Cl^-: 0.3 µS/cm -> Cl^- < 0.1 ppm

Water chemistry specifications

Conductivity limit (2):

- **limit electric currents flowing through the water in insulation hoses**
  - ~~arcing~~
  - boiling
    - loss of cooling
    - arcing

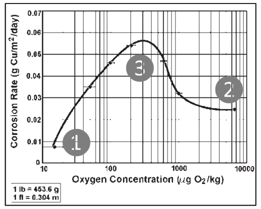


- **actual limit value specific for each case**
  - high voltage (up to 27 kV), water flow, hose geometry
- **common limit: 10 µS/cm** 🙌
  - grossly over-conservative
- **other common limits: 9.9 µS/cm, 9 µS/cm, 8 µS/cm, ...**
  - that's the OEM 10 µS/cm limit, de-escalated by management ...

Water chemistry specifications

Oxygen limits:

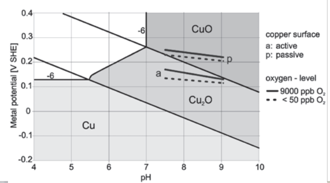
- **avoid transition zone 3**
  - high release rate
  - poorly defined direction to Cu_2O resp. CuO
- **low-oxygen systems 1**
  - keep oxidation / release as low as possible
- **high-oxygen systems 2**
  - attain moderately low release rate
  - keep oxide as much CuO as possible



Water chemistry specifications

Electrochemical Potential (ECP):

- **keep oxide type in its assigned form**
  - Cu_2O for low-oxygen chemistry
  - CuO for high-oxygen chemistry



Water chemistry monitoring

Recommended monitoring parameters

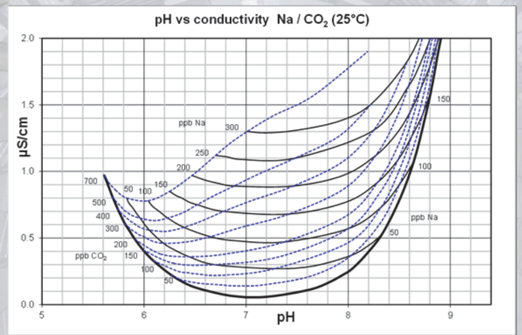
Parameter	Continuous	Periodic
Conductivity	x	
Oxygen *	x	
Copper concentration **		x
Electrochemical Potential (ECP) ***	x	
Possible chemical additives (e.g. NaOH) **		x

* oxygen monitoring not required for high-oxygen chemistry when air is continually injected into the system
** diagnostic parameters
*** tentative parameter

pH monitoring is not recommended because of problems with measurements in high-purity water
Conductivity is recommended as a substitute, using the pH/conductivity relationship

Water chemistry monitoring

Relationship between conductivity and pH



Strategies to avoid Hollow Conductor Plugging

- Lay-up when the generator is shut down (copper hollow conductors)

Options when the generator is shut down

	Leave system running	Shut pumps and leave system filled with water	Drain and dry
Short term lay-up *	x	x	
Long-term lay-up			x

* Although the 3 day limit is somewhat arbitrary, experience has shown that for most systems the water chemistry can be maintained for that length of time without circulation. Extending that time period will require monitoring the water chemistry to assure that it is held within the OEM specifications.

Lay-up option: leave system running

Pros and Cons:

- Best and safest method for lay-up
- In case of leaky stator bars, and if hydrogen overpressure is removed: → water leak into the stator
- Operating efforts and costs

Lay-up option: shut pumps but leave system filled

Pros and Cons:

- Simple, no (or only small) risk for water leak into the stator
- Uncontrollable chemistry, may deteriorate with time → only for short-term lay - up

Lay-up option: drain and dry

Implementation:

- Replace water with nitrogen
- Valve out stator from cooling water system
- A series of hard blows with compressed air
- Evacuate coil to pressure well below vapor pressure of water at coldest point
- Keep coil dry all the time (→ supervision)

☞ *Dry coil may then be exposed to air*

Lay-up option: drain and dry

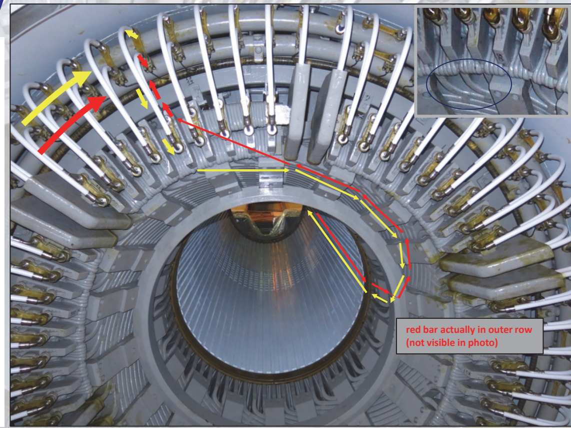
Pros and Cons:

- Best and safest long-term lay-up
- Only little supervision and maintenance required to uphold condition

- ✖ Requires considerable preparations, efforts, and discipline at shutdown of generator

Lay-up option: drain and dry

- **Draining by gravitation is not efficient:**
  In the order of 500 liters of water stay trapped in the coil
- **Vacuum drying after gravity draining:**
  Not possible to remove so much water in finite time
- ☑ **Push out the water with strong air blows**
  Vacuum then not required because the coil can be left on air *when dry*
  Nitrogen cap (not necessary) has advantage of being better supervised



Lay-up option: high oxygen chemistry generators

Lay-up is especially a main concern for low-oxygen generators:

transformation of Cu_2O into CuO may cause oxide mobilization.

But also high-oxygen units may be affected:

- entrance of air into → lower pH in the water film (by the CO_2 in air), → upsets oxide stability.
- if the generator had an out-of-specification operating history with periods of low oxygen; then the exposure to air may mobilize oxides rapidly at re-start and plug the stator.

Lay-up option: stainless steel hollow conductors

Parameter	During operation	During shutdown	
Conductivity (25°C), µS/cm	< 0.3	< 0.3 *	* if stator is left filled, or before draining
Oxygen, µg/l (ppb)	-	-	no requirement
Oxygen, µg/l (ppb)	< 10	-	
Oxygen, µg/l (ppb)	< 10	-	

→ no special procedures for lay-up required

Summary: Example on poor normal operation chemistry and poor lay-up

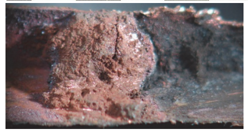
- **Low-oxygen chemistry, but 100-200 ppb O_2 during normal operation**
- **draining water and left idle in air for 2 weeks**

Result: Cross-section of a hollow conductor with oxide plug
- **the oxide flaked off (left)**
- **and re-deposited downstream within the bend (right)**

Event took place at re-start after shutdown with no lay-up
Result: meltdown of stator bar

Finalizing … instead of a conclusion

If matters did get wrong:
- **mechanical cleaning**
  - scraping, blasting, brushing …
- **chemical cleaning**
  - (acid), complexants e.g. EDTA
- ***improve chemistry and lay-up***



A deposit that was too hard to be removed.
20% Cu_2O, 5% CuO, 75% Cu_{met}
The stator bar had to be replaced

☞ **Perform corrective actions before the deposits have become too thick or too dense for non-invasive removal**