

# Corrosion and Deposits in Water-Cooled Generator Stator Windings: Part 1: Behaviour of Copper

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## ABSTRACT

The most common and severe problem that has arisen with generator water cooling throughout its more than 50 years of history is plugging of copper hollow conductors. A 4-step model of the occurrence of this plugging was developed to indicate the influencing parameters. The steps are oxidation of the copper surface, release of the oxidized copper, migration of the released copper, and re-deposition of the migrating copper. It is observed that these steps are influenced by water chemistry as well as by system and component design. From the operating side, adherence to a suitable water chemistry regime as well as proper lay-up practice help to avoid or mitigate flow restrictions.

## INTRODUCTION

The use of high-purity water results in relatively few chemistry and materials issues in generator water cooling. Of the few problems that arise, flow restrictions by copper oxide deposits have been observed in about 10 to 20 % of the water-cooled generators. This paper explores the mechanisms and influencing factors of such flow restrictions.

This article is part of a series of five articles to appear in this journal on corrosion and deposits in water-cooled generator windings [1–5].

## BACKGROUND

Cooling of the generator winding is achieved by inserting strands with small cooling channels between the solid copper strands used for conducting electricity, commonly termed hollow conductors. Traditionally, they are made of copper, but stainless steel is also used.

There is no problem regarding corrosion with the use of stainless steel in high-purity water [6]. With copper however the most common corrosion-related problem is plugging of hollow conductors and strainers with copper oxides [7,8]. It is estimated that about 10 to 20 % of the 2 000 water-cooled generators worldwide (not including the former USSR and China) suffer from related flow restrictions sooner or later within the first 25 years of operation.

In the absence of oxygen, copper is stable and does not corrode in pure water [9]. However, together with oxygen, copper oxides are formed that slowly dissolve in the water. In order to remove the dissolved copper as well as other impurities, purification in a side-stream mixed bed was foreseen. To limit the copper oxidation, two distinctly different approaches were chosen by the original equipment manufacturers (OEMs):

- low-oxygen chemistry: keeps the oxidation of copper as low as possible
- high-oxygen chemistry: allows the formation of an oxide layer that slows down further oxidation

Low-oxygen chemistry was chosen by Siemens, Germany, Brown, Boveri & Cie, Switzerland, and later Westinghouse Electric Corporation (WEC), USA, and their technology followers (licensees etc.), high-oxygen chemistry by General Electric Company (GE), USA, and followers. It was also the standard in the former USSR and in China. The British companies (Associated Electrical Industries (AEI), General Electric Company (GEC), and C. A. Parsons and Company) opted for a hybrid approach, by having the system closed to air, but with a dead-end head tank open to atmosphere. Such a system was in fact of the low-oxygen type, but with frequent incursions of air-saturated water.

In some plants of the former USSR turbine condensate was also used, either with ammonia or with ammonia having been removed, but detailed information is not available.

An alternative strategy to counteract the occurrence of plugging was found in the 1970s in the alkalization of the cooling water [10] and it was first implemented in 1979 [11,12]. Since then, more than 260 of the 2 000 generators mentioned above are using this technology.

### MECHANISM OF PLUGGING OF COPPER HOLLOW CONDUCTORS

In water, copper together with oxygen reacts to  $\text{Cu}^+$  and  $\text{Cu}^{2+}$  hydroxides and oxides. The resulting layers are very thin (in the order of  $1\ \mu\text{m}$ ) and will not cause any flow restrictions. However, if the deposits are released to the water, and re-deposit locally at preferential sites, the hollow conductor cross section will be impaired there and in extreme cases will even plug up fully (Figure 1).



Figure 1:  
Water chamber with severely plugged ends of the hollow conductors.

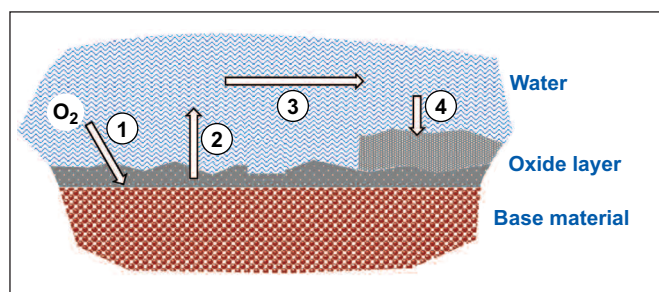


Figure 2:  
Schematic of the mechanism of hollow conductor plugging: (1) oxidation of the copper surface, (2) release of the oxidized copper (particle or ion), (3) transport of the released copper, (4) re-deposition of the migrating copper.

The mechanism of growth of flow restrictions can be separated into four steps (Figure 2):

- (1) Oxidation of copper surfaces
- (2) Release of oxidized copper
- (3) Migration of released copper
- (4) Re-deposition of migrating copper

Only the combination of these four steps leads to flow restrictions. Water chemistry is one of the parameters of influence, but one must remember that other parameters also have an important impact. Not all plugging problems can be blamed on bad chemistry; good chemistry may not bring a cure for everything.

While the mechanisms of steps (1) and (2) are quite well understood and step (3) is rather self-evident, only little research is available on step (4), that is, on the question why the copper deposits and at which locations.

#### (1) Oxidation of the copper

Under low-oxygen conditions, all oxygen entering the system is fully consumed by the copper surfaces. Otherwise, any incoming oxygen would add up in the system and the oxygen concentration in the water would increase towards saturation, which does not happen in low-oxygen systems. The full consumption of oxygen is completely independent of any low-oxygen water chemistry scheme (e.g. alkaline treatment).

Under high-oxygen conditions, a copper oxide layer forms and hinders further access of oxygen to the copper, thus slowing down the oxidation rate. This oxide layer is steadily dissolved in the water. The thickness of the oxide layer is then determined by the balance between the oxidation rate and the dissolution rate.

In low-oxygen systems and in neutral-pH systems, cuprous oxide ( $\text{Cu}_2\text{O}$ ) will be predominant, while in high-oxygen and in alkaline systems, the oxide will be mainly cupric oxide ( $\text{CuO}$ ). Figure 3 illustrates that all operating points are close to the  $\text{Cu}_2\text{O}/\text{CuO}$  boundary in the Pourbaix (potential-pH) diagram for the  $\text{Cu}-\text{H}_2\text{O}$  system [13]. The Pourbaix diagram is designated for equilibrium conditions, which are different from the dynamic conditions found in a cooling system. Therefore, a changing and potentially unstable mixture of oxides may be present in a generator.

The morphology of the oxides is also influenced by the system water chemistry. Figure 4 gives an example of a specimen with dense polyhedral oxides, typical for high-oxygen or alkaline water chemistry, and another one with flower-shaped needles, typical for low-oxygen or neutral water chemistry.

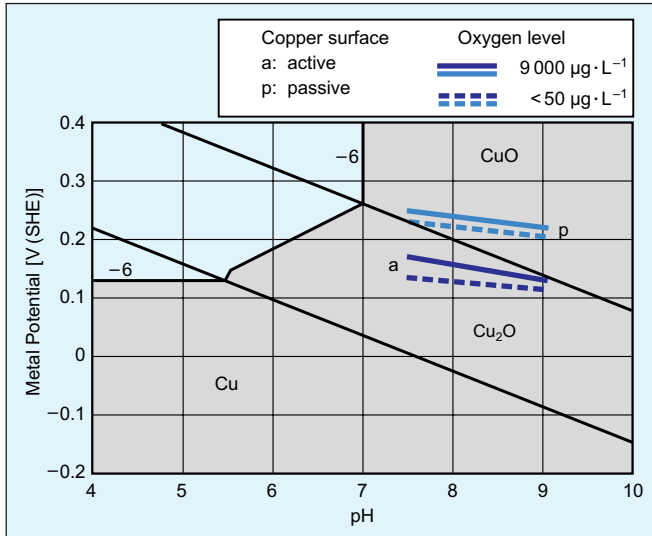


Figure 3: Pourbaix diagram and potential of passivated (black CuO layer) and active (freshly pickled) copper specimens [13].

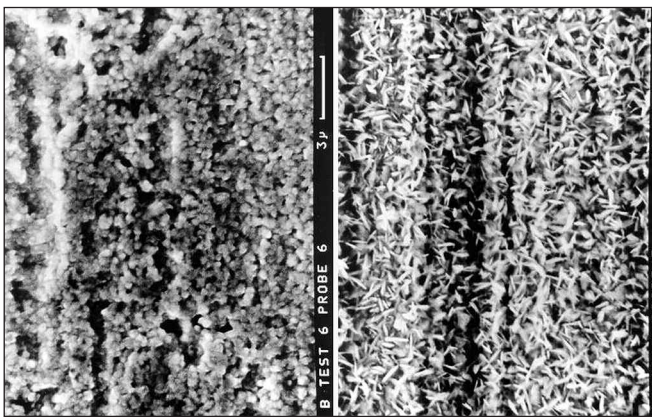


Figure 4: Copper oxides: dense polyhedrons (left) and flower-shaped needles (right) formed in alkaline and in neutral water, respectively [13].

## (2) Release of the oxidized copper

The copper is released from the copper surfaces either as particles (e.g. oxides, hydroxides) or dissolved as ions ( $\text{Cu}^+$  and  $\text{Cu}^{2+}$ ).

Particle release is usually related to spalling of deposits, for example by phase changes (from  $\text{Cu}^+$  to  $\text{Cu}^{2+}$ ) during transient operation like inadequate lay-up, by changes in the electrochemical potential (ECP) [14], or by mechanical stresses caused by high water velocity or turbulence. Dissolution of copper oxides (see below) may also release particles that were bonded by the oxide.

In water and in the presence of oxygen, copper dissolves by the formation of  $\text{Cu}^+$  and  $\text{Cu}^{2+}$  ions. Depending on solubility limits, the copper ions are transformed into

precipitated copper oxides and copper hydroxides. The dissolution progresses until the solubility limit is reached. Then a covering layer of precipitated copper oxide/hydroxide is formed. The release rate of copper, symbolized by step (B) in Figure 5, will then depend on how much dissolved  $\text{Cu}^+$  or  $\text{Cu}^{2+}$  is removed from the boundary layer and replenished by the oxidation (step A).

The release rate can then be described by mass transfer kinetics:

$$dm/dt = k \times (C_B - C_W) \quad (1)$$

where

- $dm/dt$  mass transferred per unit of time (release rate)
- $k$  mass transfer coefficient
- $C_B$  copper concentration in the oxide/water boundary layer
- $C_W$  copper concentration in the bulk liquid

The mass transfer coefficient  $k$  is determined by the mechanical transport with the flowing water and by diffusion. It includes the effect of various parameters, such as the water velocity and turbulence, flow geometry, surface finish and temperature.

$C_W$  is mainly determined by the effect of the mixed bed, step (3).

The role of chemistry is only within  $C_B$ . The copper concentration in the oxide/water boundary layer will be at or near saturation, which corresponds to the solubility limit of copper ions, which depends on chemical (for instance pH) and thermodynamic parameters, Figure 6 [15].

In reference [15] it is observed that while the solubility of copper oxides increases only moderately with tempera-

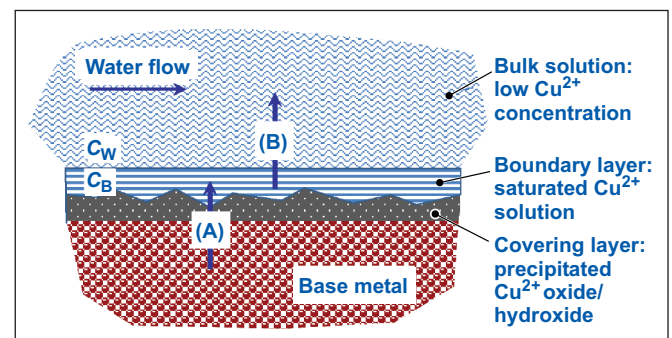


Figure 5: Mechanism of the oxidation and release of copper in water:  
 $C_W, C_B$  Concentration of  $\text{Cu}^{2+}$   
 (A) Oxidation  $\text{Cu} + \text{O}_2 + \text{H}_2\text{O} \rightarrow \text{Cu}^{2+}$  oxide/hydroxide (dissolved);  
 precipitation of surplus into covering layer (solid)  
 (B) Dilution of the boundary layer: mass transfer from the saturated boundary layer into the water flow.

ture, the release rate shows a stronger increase. The difference is evidently caused by the mass transfer coefficient, which causes an additional increase with temperature.

It is useful to remember that other parameters besides water chemistry like flow velocity (Figure 7) and temperature also have an influence on the release rate. Such parameters are usually related to design.

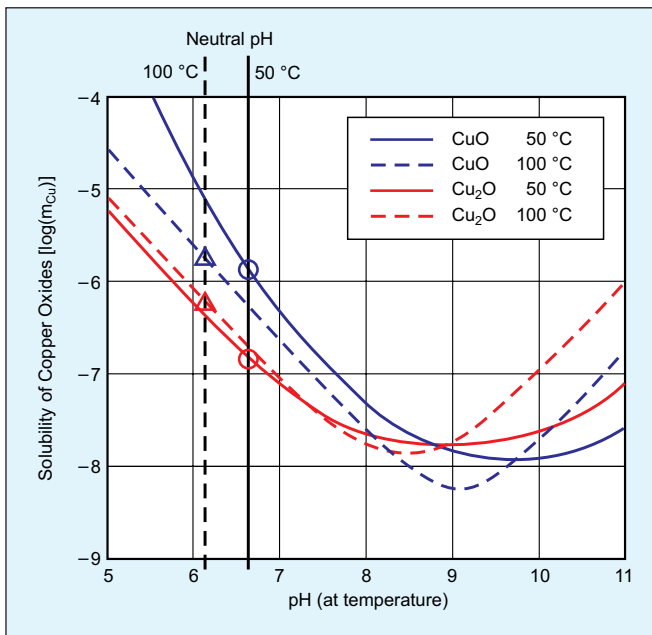


Figure 6: Copper solubility as a function of pH and temperature [15].

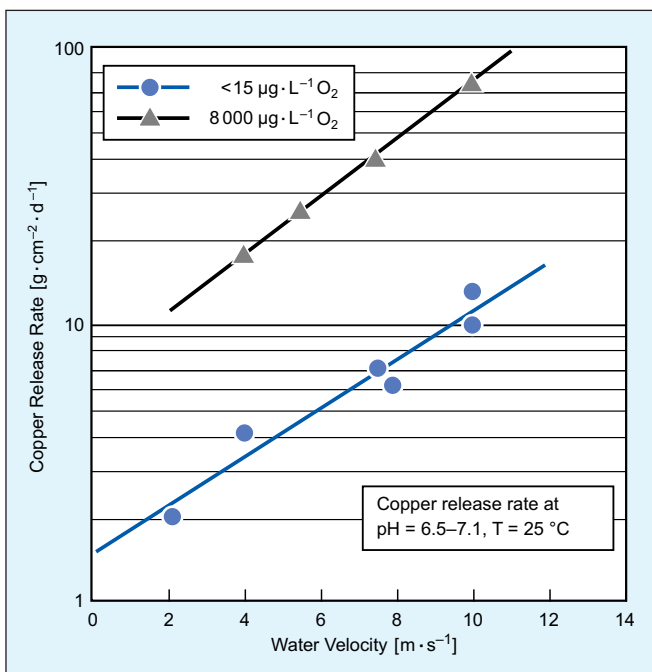


Figure 7: Copper release rate as a function of water velocity.

Figure 8 shows that with low oxygen concentrations, the release rate rises steadily with the oxygen concentration. Here the release rate is directly dependent on the oxidation rate. At high oxygen concentration, the release rate levels out at a relatively low value; this is due to the slowing down of the reaction by the oxide layer that has grown in the high-oxygen system. It is important to remember that the release rate with high-oxygen chemistry is nevertheless larger than with low-oxygen chemistry. Figure 9 illustrates that the release rate decreases when the pH is raised to 8.0 or 8.5.

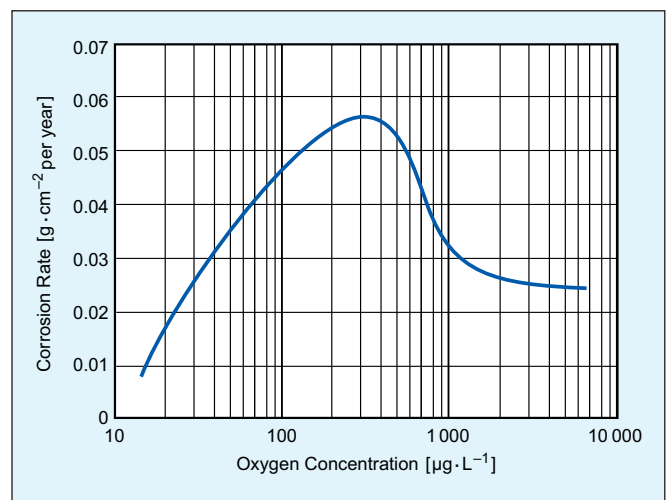


Figure 8: Copper release rate as a function of oxygen concentration [10].

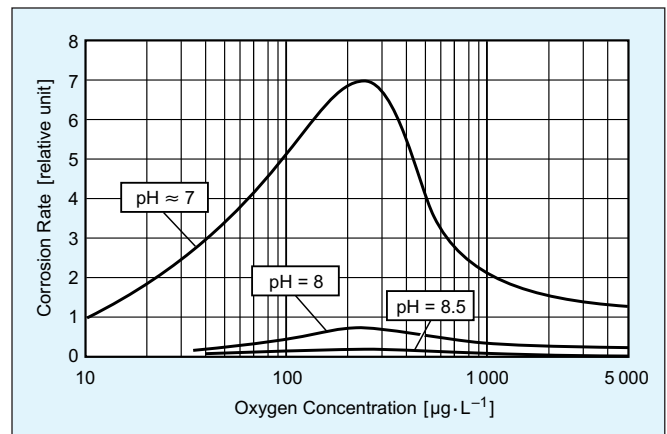


Figure 9: Copper release rate as a function of oxygen concentration and pH [11].

### (3) Migration of the released copper

Once the copper is released into the water, it is circulated in the system until it is absorbed somewhere. This is done either by the mixed bed, by the filter, or by deposition, which is predominantly inside the copper hollow conductors of the stator bars.

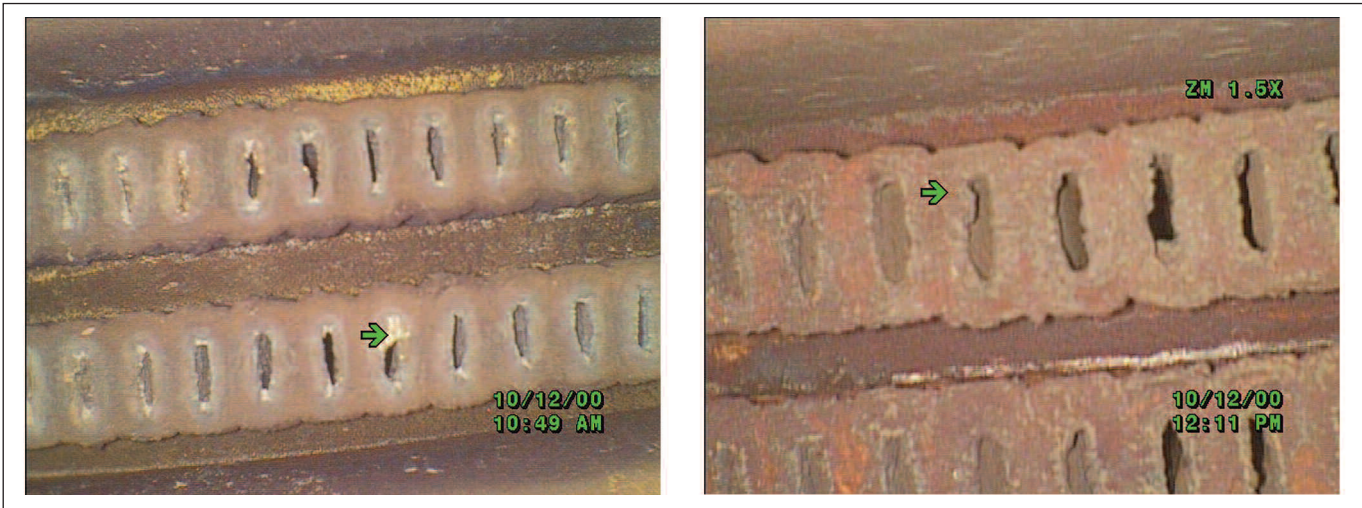


Figure 10: Crystallized oxide deposits at the inlet (left) and outlet (right) of the hollow conductors.

The copper concentration in the system is determined by the equilibrium between the release rate and the removal rate.

Consequently, a higher mixed-bed flow rate and an efficient full-flow filter with fine mesh cartridges are effective for lowering the copper concentration in the cooling water and leaving less copper for deposition in the winding.

#### (4) Re-deposition of the migrating copper

Investigations on oxide deposits show that re-deposition preferentially takes place at the hollow conductor inlets and outlets (Figure 10), and also at places of flow disturbances inside the hollow conductors (Figure 11), that is, at places of elevated turbulence. These deposits are mainly locally grown crystals, often with oxide particles embedded. Sedimentation of particles is usually a secondary effect at flow restrictions by crystal growth.

There is only little published research on the mechanism of re-deposition. Basically, the same effect as in step (2) (copper release) takes place. With re-deposition, the mass transfer however goes in the opposite direction ( $C_W > C_B$ ), as shown in Figure 12.

In order to obtain crystallization, the concentration in the water must be at the solubility limit, that is,  $C_B = \text{saturation}$ . Because the crystallization process takes copper ions away from the boundary layer,  $C_B$  will decrease. In order for the crystallization process to continue,  $C_B$  will therefore need to be replenished from  $C_W$ . Here the same mass transfer parameters as for Eq. (1) are applicable. This could explain why the crystallization preferentially takes place at elevated water turbulence. This indicates that stator bar design may influence the tendency for the precipitation of copper oxides.

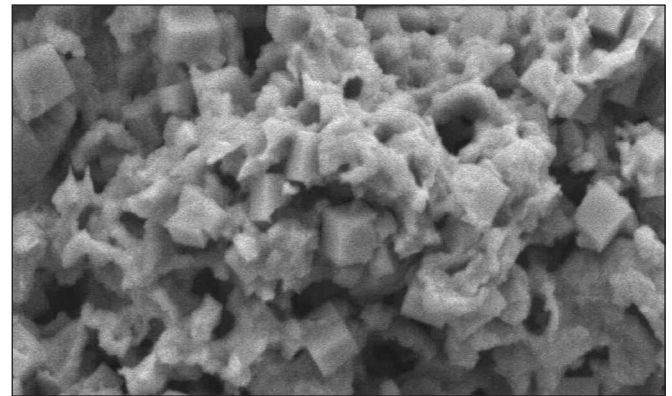


Figure 11: Crystallized oxide in a deposit inside a hollow conductor. The bottom edge of the photo measures 6  $\mu\text{m}$ .

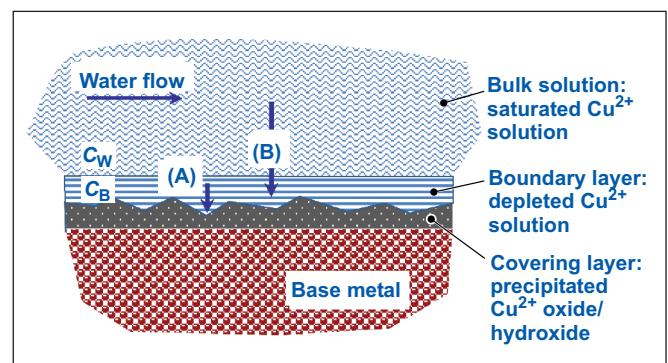


Figure 12: Mechanism of the precipitation of copper in water:  
 $C_W, C_B$  Concentration of  $\text{Cu}^{2+}$   
 (A) Precipitation from the saturated boundary layer, resulting in a depletion  
 (B) Replenishment from the boundary layer: mass transfer from the saturated bulk solution into the depleted boundary layer.

### SOLUTIONS TO AVOID HOLLOW CONDUCTOR PLUGGING

The influencing parameters in steps (1) to (4) as outlined in Figure 2 offer solutions for avoiding or mitigating excessive deposits in the hollow conductors. This article will be focused on actions that can be taken by plant operation. It should however be kept in mind that this is not the complete picture as some root causes are related to the design of the stator bars and the cooling water system, e.g. flow geometry and velocity, mixed bed flow rate etc. [8]. Many problems originating in design cannot be mended by plant operation efforts.

Good water chemistry during all operating conditions is essential to avoid excessive oxide deposits. This comprises normal operation as well as conditions when the generator is shut down.

#### Water Chemistry during Normal Operation

Today there are five different water chemistries applied, each one following its own strategy (Table 1).

Their domain of application is summarized in Figure 13. It should be mentioned that all these water treatment regimes have their success, but none is without failures.

Low-oxygen treatment is obtained by having the system sealed against air, for example, by a hydrogen or nitrogen gas blanket at a pressure slightly above atmospheric. High-oxygen treatment is obtained by leaving the system open to air and forced aeration.

The most common causes for elevated oxygen levels in low-oxygen systems are ingress of air by leaky flanges, valves, or pump sliding seals, use of significant quantities of aerated make-up water, opening parts of the system for maintenance, or inadequate lay-up. It must also be recognized that air may even be sucked into an over-pressured

system by a water-jet effect. Gas-to-water leakage within the stator can also lead to detrimental oxygen ingress with the impurity of hydrogen.

Common causes for insufficient aeration in high-oxygen systems are hydrogen leaks into the water that replace the air blanket of the water tank. In addition, oxygen is consumed slowly by the copper surfaces in the system. Regular or continuous feed of air is required to maintain high oxygen levels. In order to avoid acidic pH, the air should be filtered for carbon dioxide.

Alkaline pH is achieved by a controlled addition of NaOH to the cooling water [16]. The target value is a pH of 8.5–9.0 [7].

The "cationic purification" method defies the strategies of all the other types of water treatment. The system is kept fully aerated without carbon dioxide removal, which will result in a slightly acidic pH, ~ 6.0– 6.5, due to the carbon

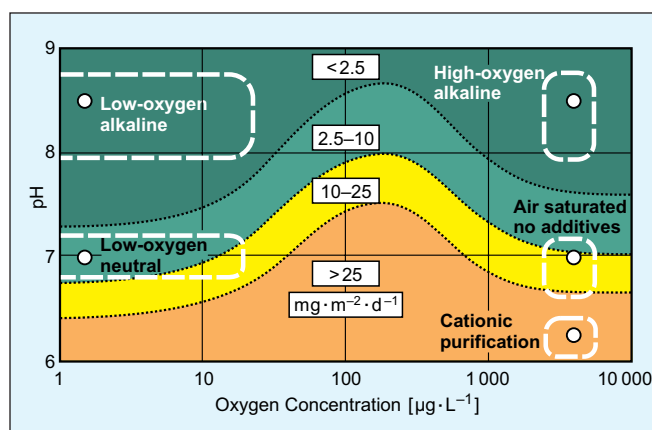


Figure 13: Summary of copper release rates as a function of oxygen concentration and pH showing operating areas of the different water chemistry regimes [2] (temperature 45 °C, flow velocity 2 m · s<sup>-1</sup>).

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 <sup>a</sup>			x	x

Table 1: Strategies for normal-operation water chemistry to prevent plugging of the stator conductors.

x Target for the respective water treatment.

<sup>a</sup> Treatment for temporary use only.

dioxide from the air. Électricité de France (EdF), France, has implemented this treatment successfully as a temporary treatment on some generators in their nuclear generator fleet [17]. It should be noted that this treatment requires profound knowledge of copper solubility and deposition criteria, as well as expert supervision. Poorly controlled, there is the risk of material damage.

Consideration has also been given to the use of reducing agents or inhibitors for low-oxygen cooling water. Potential problems are the incompatibility of the agent with the low-conductivity limits required for generator operation, and the need for its replenishment when consumed or removed by the system's mixed-bed filter. Moreover, unexpected side effects may occur. Some inhibitors have caused a compacting of oxide deposits, thus rendering them more difficult to remove. Consequently, there is good reason to recommend maintaining the simple chemistry of the copper/water system.

Some generators have oxygen scavengers combined with the side-stream mixed-bed filter. Techniques are either scavenger loaded ion exchangers (sulphite, ascorbic acid, hydrazine), or the use of palladium-catalysed resin to recombine oxygen with the dissolved hydrogen gas

[11,18]. These side-stream devices have the disadvantage of having a slow "clean-up" time constant, and oxygen may more rapidly be consumed by the winding than by the scavenger. In generators with slow oxygen consumption (for example with alkaline treatment) or large side-stream water flows, this technique may nonetheless be interesting. However, it requires extra supervision and maintenance.

In specific cases it may be useful to convert the water chemistry from one regime to another. The associated transition in oxide structure may render the oxide layers unstable. Such a step should therefore be carefully planned, and take consideration of design, materials, available hardware, and the current condition of the hollow conductors [19,20]. Usually a cooling water system and its components are designed for a specific water treatment regime. When changing the regime, changes in the cooling water system may be required. In order to achieve a defined oxide structure, a chemical cleaning should be considered at the beginning of the conversion.

The water chemistry specifications for the various types of treatment are listed in Table 2 to Table 4. These tables are based on references [6], [7], and [8].

Parameter		Normal Operating Value	Short-Term Action Level	
Conductivity (25 °C)	[ $\mu\text{S} \cdot \text{cm}^{-1}$ ]	$\leq 0.5$	$> 10$	Neutral water treatment
		$\leq 2$	$> 10$	Alkaline water treatment <sup>a</sup>
Oxygen	[ $\mu\text{g} \cdot \text{L}^{-1}$ ]	$\geq 2\ 000$	$< 1\ 000$	
ECP <sup>b</sup>	[mV(SHE)]	$> 315$	$< 305$	

Table 2:

Stator cooling water specifications for high-oxygen chemistry.

<sup>a</sup> Alkaline water treatment means pH 8.5–9.0.

<sup>b</sup> Electrochemical potential (ECP): tentative specification.

Parameter		Normal Operating Value	Short-Term Action Level	
Conductivity (25 °C)	[ $\mu\text{S} \cdot \text{cm}^{-1}$ ]	$\leq 0.5$	$> 10$	Neutral water treatment
		$\leq 2$	$> 10$	Alkaline water treatment <sup>a</sup>
Oxygen	[ $\mu\text{g} \cdot \text{L}^{-1}$ ]	$\leq 20$	$> 50$	"as low as possible"
			$> 10$ above normal	"start troubleshooting"
ECP <sup>b</sup>	[mV(SHE)]	$< 223$	$> 266$	

Table 3:

Stator cooling water specifications for low-oxygen chemistry.

<sup>a</sup> Alkaline water treatment means pH 8.5–9.0.

<sup>b</sup> Electrochemical potential (ECP): tentative specification.

Parameter		During Operation	During Shutdown	
Conductivity (25 °C)	$[\mu\text{S} \cdot \text{cm}^{-1}]$	< 0.3	< 0.3 <sup>a</sup>	
Oxygen	$[\mu\text{g} \cdot \text{L}^{-1}]$	–	–	no requirement
Copper	$[\mu\text{g} \cdot \text{L}^{-1}]$	< 10	–	
Iron	$[\mu\text{g} \cdot \text{L}^{-1}]$	< 10	–	

Table 4:

Stator cooling water specifications for windings with stainless steel hollow conductors.

<sup>a</sup> If stator is left filled, or before draining.

So far the significance of the oxygen concentration has been discussed. The specifications however also include limits for conductivity. Traditionally, a limit of  $1 \mu\text{S} \cdot \text{cm}^{-1}$  was used for normal operation, as this was a simple number and a value easily achieved in a closed loop with mixed-bed purification. A lower value of  $0.5 \mu\text{S} \cdot \text{cm}^{-1}$  is used nowadays in order to limit excursions in pH [8,21,22]. In addition, a short-term action level is set to avoid boiling in the electrically insulating water supply hoses to the stator, which are at high voltage. Such boiling would reduce water flow and thus degrade cooling, and could give rise to a destructive electric discharge. The limit given in the tables is a generic one, and subject to the respective technical design.

The ECP specification is discussed in references [23] and [24].



Figure 14:

Cross section of a hollow conductor with an oxide plug. The oxide flaked off (left) and re-deposited downstream (center right). The event took place after shutdown with no lay-up.

Limits for chloride and copper are given to avoid corrosion on stainless steel hollow conductors.

### Lay-up during Shutdown

Corrosion resistant materials in the stator cooling water system (SCWS) together with the high-purity water do not necessitate special corrosion protection for lay-up. However, many water-cooled generators worldwide have experienced plugging of hollow strands or clogging of strainers because of the presence of oxide migration or ingress of  $\text{CO}_2$ , often having closely coincided with outages. An example is given in Figure 14. Often the consequences of inadequate lay-up may be cumulative and only realized several years later.

Stators with stainless steel hollow conductors do not require special lay-up except that the water in the system should have a low conductivity before draining; Table 4 and [6].

Table 5 lists the recommended options for lay-up.

**Leave the system running** If the generator is not the cause of the outage, the gas and SCWS can remain in service conditions, even for long-term lay-up. In such a case, the stator water chemistry has to be properly upheld and monitored. Because this type of attention may not be guaranteed during long periods of plant shutdown, this option is not included as a standard option for long-term

	Leave System Running	Shut Pumps and Leave System Filled with Water	Drain and Dry
Short-term lay-up <sup>a</sup>	x	x	
Long-term lay-up			x

Table 5:

Options for lay-up.

<sup>a</sup> Short-term means 3 days or less. The 3-day limit is not rigid and may be extended by a few days or even decreased depending on qualified experience.



lay-up. However, this option is perfectly viable and may be preferable for plants that lack the resources or procedures to facilitate appropriate drying of the winding.

Generators with pre-identified stator bar end leaks or where leaks are suspected are a major concern when the gas pressure is lowered below the water pressure and the pumps are in operation. For these generators, leaving the system running is only viable with a pressurized cover gas in place. Other generators may operate the SCWS at the owner's prerogative with the water pressure higher than the gas pressure. Note that during purging of the hydrogen, replacing it with CO<sub>2</sub>, and finally with air, the pressure of the cover gas is seldom kept above the water pressure. Generally, this is acceptable because the water pressure is higher than hydrogen only for a short time.

**Shut off pumps and leave system filled with water** This option presumes that the original stator water chemistry is maintained during the lay-up period. 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 of the water chemistry to assure that it is held within the OEM specifications.

For this option it is necessary to assure that the generator stays filled with water up to the top. This may be easier for systems with a positive pressure water head, that is, where the water level is geodetically higher than the uppermost point of the stator. In systems with a negative pressure water head, that is, when a water tank is situated lower than the stator, a sufficient gas overpressure can avoid vacuum in the stator and with this the risk of air in-leakage. Other measures are also possible, for example the use of isolation valves to the winding.

**Drain and dry** Copper surfaces, either blank or with oxide, do not change into a deteriorating condition when dry. Reactions, however, take place when they are wet, readily within a time frame of a few hours.

Simple draining of the stator will not make the winding dry. A good part of the stator bars will still be filled with water and the drained bars will be wet and filled with moist air.

This is especially a main concern for low-oxygen generators, where transformation of Cu<sub>2</sub>O into CuO may cause oxide mobilization (Figure 2, item (2)).

High-oxygen units are also affected, but with different mechanisms. Entrance of air into a partially drained stator winding will lower pH in the water film (by the CO<sub>2</sub> in the air). Stator bars left filled with water will transform to a low-oxygen environment, because the oxygen is consumed by the copper. Such chemistry changes will upset oxide morphology and stability. Another risk factor

appears when the generator has 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.

In order to properly lay up a water system or to evacuate the system for the performance of a dielectric resistance and withstand test (DC or AC Hipot test), a method of removing all of the moisture from copper surfaces must be employed. The method consists of the following basic steps:

- Draining the water from the system
- Isolating the components with copper surfaces from the rest of the system
- Blowing-down with a series of strong blasts with oil-free compressed air
- Pulling a vacuum on the system
- Monitoring dew point or insulation resistance

Vacuum drying alone, without previous blow-out of the water, will not be successful. Several hundred litres of water will still remain in the winding after draining, which is too large an amount to be removed via vacuum pump.

**Refilling** The safest way to refill the stator cooling water system is to assure that the water in the system is at the proper level of dissolved oxygen during and at the completion of filling. With low-oxygen chemistry, the system should first be evacuated and then filled with nitrogen. The water, when added, will then not be in contact with air to pick up oxygen.

## WATER CHEMISTRY MONITORING

Table 6 lists the recommended chemical monitoring parameters and their frequency. Periodic means once a week, or more when instabilities in the values are observed.

The interpretation of these data is treated in other publications [21,22,24].

Other chemistry parameters may of course also be routinely monitored, but their value would need to be scrutinized regarding usefulness. Too many data points may lead to a situation with more questions than answers.

## MANAGING FLOW RESTRICTIONS

If the generator nevertheless develops flow restrictions, corrective actions can still be taken. The sooner they are taken, the more successful they are. It is therefore impor-

Parameter	Continuous	Periodic
Conductivity	x	
Oxygen <sup>a</sup>	x	
Copper concentration		x
Electrochemical potential (ECP)	x	
Possible chemical additives (e.g. NaOH)		x

Table 6:

Recommended parameters for routine chemical monitoring of the cooling water system. pH is not included because in high-purity water it would require instrumentation that is not compatible with the requirements in the cooling water system.

<sup>a</sup> Oxygen monitoring is not required, but still recommended in high-oxygen systems when air is continuously injected into the system.

tant to monitor the generator for flow restrictions all the time. Details are given in the following article of this series on generator water cooling [3]. Physical key parameters for monitoring are:

- winding and bar temperatures
- winding water flow
- $\Delta p$  (pressure difference) winding inlet to outlet
- $\Delta p$  over filter and strainer (if there is one)
- $\Delta p$  gas to water
- gas-to-water leakage
- consumption of make-up water

If the winding shows indications of flow restrictions, it is recommended to take swift corrective action. Mechanical and/or chemical cleaning are effective in removing flow restrictions. Details are given in another article of this series on generator water cooling [4]. Cleaning however does not eliminate the root cause. The control of operation practice and water chemistry, and possibly also the design parameters/features, should then be critically reviewed in an effort to reduce or eliminate plugging in the future.

Managing flow restrictions at an early stage reduces the risk of severe plugging of conductors that may be very difficult to remove later on.

## PRACTICE

There are presently about 2 000 water-cooled generators worldwide (excluding the former Soviet Union and China). About 50 % operate under high-oxygen chemistry, and 50 % under low-oxygen chemistry. Included are 10 to 15 % of the plants with alkaline treatment and an estimated 5 to 10% with stainless steel hollow conductors.

With this collective experience, it is still not possible to take a straight position for one of these water chemistry options. As already noted above, all these water treatment regimes give good performance, but none is without failures. This concerns every major OEM.

The following case studies illustrate typical events leading to problems. These examples refer to generators from different major OEMs where we were involved in the subsequent troubleshooting and chemical cleaning.

### Plugged Stator Bars Result in Forced Outage

440 MVA generator in a coal-fired power plant. Low-oxygen chemistry.

This generator had operated for about 5 years. Two weeks after an outage, the stator tripped by ground-fault. At the following inspection, it was found that two stator bars had overheated. An investigation of these bars showed deposits of  $\text{Cu}_2\text{O}/\text{CuO}$  flakes (Figure 14). In a sister unit, the same type of incident led to the meltdown of two stator bars under transient load conditions.

Root Cause: Low-oxygen chemistry was poorly implemented; the stator cooling water had long-term excursions to higher oxygen levels. Oxygen monitoring was only sporadic. During normal operation, the elevated oxygen level led to  $\text{Cu}_2\text{O}$  deposits, which transformed partially to  $\text{CuO}$  during the outage when the wet hollow conductors were exposed to atmosphere. This phase change initiated the oxide exfoliation at re-start, and soon afterwards the deposits caused the generator to fail due to insufficient cooling.

The overheated bars had to be replaced.

### Hollow Conductor Plugging due to Hydrogen Leak

512 MVA generator in a coal-fired power plant. Low-oxygen chemistry.

Within a period of 3 months, stator water flow deteriorated from  $98 \text{ m}^3 \cdot \text{h}^{-1}$  (430 gpm) to less than  $68 \text{ m}^3 \cdot \text{h}^{-1}$  (300 gpm).

Root Cause: A large leak ( $14 \text{ m}^3$  (500  $\text{ft}^3$ ) per day) from a broken flexible metal cooling water tube introduced large

amounts of hydrogen with enough trace impurity oxygen to result in the stator hollow conductors becoming partially plugged by oxide.

Subsequent repair of the damaged cooling water tube and chemical cleaning of the hollow conductors restored cooling water flow conditions to normal.

### Hollow Conductor Plugging due to Uncontrolled Oxygen Concentration

960 MVA generator in a nuclear power plant. High-oxygen chemistry was implemented by maintaining the stator water tank vent open to air. No forced aeration was in place to ensure oxygen saturation.

Over the years, there were no noticeable changes in the differential pressure across the generator stator. Right after restart from an outage, pressure drop deteriorated. Finally, the flow regulation was fully open and the flow deteriorated from its normal value of  $139 \text{ m}^3 \cdot \text{h}^{-1}$  (610 gpm) at the rate of  $7 \text{ m}^3 \cdot \text{h}^{-1}$  (30 gpm) per day. Due to insufficient cooling of the stator the plant load had to be reduced during prime demand for several days. Before the outage, the level of dissolved oxygen had been found to fluctuate between less than  $0.1 \text{ mg} \cdot \text{L}^{-1}$  and  $3 \text{ mg} \cdot \text{L}^{-1}$ , instead of being at a saturation of  $4\text{--}5 \text{ mg} \cdot \text{L}^{-1}$ .

Root Cause: After initial high-oxygen chemistry, oxygen decreased to low levels and subsequently the plant had been operating for extended periods under low-oxygen conditions (oxygen levels may decrease by oxygen consumption of the copper surfaces or by hydrogen leakage that replaces the air blanket in the water tank). During and after the outage the SCWS was again exposed to higher oxygen levels. This variable water chemistry caused a mobilization of the oxides that then plugged the hollow conductors.

On-line chemical cleaning of the hollow conductors restored cooling water flow conditions to normal. In such systems it is recommended to perform a forced oxygenation of the stator water by means of injection of  $\text{CO}_2$ -free air.

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### FURTHER READING

Up-to-date literature to supplement the present article in more detail can be found in the following references.

General information and practical issues:

- EPRI guide on maintenance of generator stator cooling system [8]
- CIGRE guide on stator water chemistry management [7]
- IAPWS guide on generator cooling water chemistry [25]
- Changing stator cooling water chemistry [19]

Scientific background:

- Behaviour of copper [15]
- Measurement of the electrochemical potential (research) [23]
- Measurement of the electrochemical potential (case study) [24]
- Effect of chemical cleaning on system materials [26]

Monitoring:

- Interpretation of chemistry data [22]
- Chemistry-related monitoring [21]
- Chemistry instrumentation [27]
- Monitoring for flow restrictions [3]

Alkaline treatment:

- Overview of alkalization [16]
- Loss of alkalization [28]

Removal of flow restrictions:

- Generator cleaning [4]

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