

# Corrosion and Deposits in Water-Cooled Generator Stator Windings: Part 3: Removal of Flow Restrictions

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## ABSTRACT

Flow restrictions in generator stator bar hollow conductors can be removed either mechanically or chemically. Both methods have their advantages and disadvantages and in certain cases only a combination of both leads to success.

Mechanical cleaning can open up completely plugged hollow conductors at the inlet or outlet of the bars, while chemical cleaning thoroughly removes all copper oxides, also within the bars. However, as with all chemical cleaning methods, there must be access for the chemicals to the copper oxide deposits so the chemicals can dissolve and remove the plugging.

To prevent metallic deposits, it is important that the chemical cleaning be performed under oxidizing conditions. Additionally, it might also be useful to apply a post-cleaning surface treatment under certain conditions.

It is recommended to take any kind of plugging seriously and to start reacting when first signs of plugging occur. Once severe conditions have developed, this might lead to power downrates, a decrease in insulation lifetime, forced outages or in the worst case even irreversible damage to the generator.

## INTRODUCTION

Flow restrictions in hollow conductors of water-cooled generators are most commonly caused by copper oxide deposits but may also be caused by various debris that has entered the recirculating water, or even by mechanical deformation of the hollow conductors. The decreasing heat transfer results in local hot spots in the winding, decreased insulation lifetime, load limitations and potential forced outages and irreversible damage to the generator. To prevent these potentially serious financial losses, it is useful to have options for removing the flow restrictions.

This is the fourth part in a series of five papers to appear in this journal on corrosion and deposits in water-cooled generator windings [1–5]. This information has also been included in more detail in EPRI publications on this subject [6,7].

## HISTORY

Water cooling of generators had its beginning in the 1950s, and since the early 1960s, more and more units have been installed. It was not until the early 1970s that flow restrictions due to copper oxide deposits were first reported. By the mid 1970s most major manufacturers had tried one or another type of hollow conductor cleaning. There are no clear publications documenting this development as its full magnitude was not yet known at that time.

The first chemical cleanings were done with strong acids like sulphuric or phosphoric acid. As these acids do not effectively dissolve cuprous oxide, oxidizing substances and complexing agents were considered.

In 1977 Seipp conducted the cleaning of a stator water system with ammonium persulphate, which intrinsically includes an acid as well as an oxidizer. Although very effective, the quantities of base metal dissolved (some 20–40 kg) prompted the development of other methods.

In 1980 Gamer and Seipp (Brown Boveri) successfully applied complexing agents in combination with an oxidizer [8] and this was further developed throughout its first successful application. In 1996 the first on-line cleaning was conducted at the 1350 MVA Seabrook generator; the chemical cleaning was carried out while the generator was operating at full load.

Today different methods and acronyms are used by the industry: mechanical cleaning, reverse flow flushing, or chemical cleaning by complexing agents, acids or complexing acids.

## CRITERIA FOR CONSIDERING GENERATOR CLEANING

A significant number of utilities have taken proactive measures against hollow conductor fouling and performed chemical cleaning as part of their preventive maintenance plan.

Table 1 lists criteria for when, at the latest, cleaning of the hollow conductors should be considered. As this table is of a general nature, the listed values are generous and should be narrowed for the individual cases.

Although some of the cleaning methods seem to require significant outage time, it must be considered that this is minor compared to the consequences of a related gen-

erator failure. Preventive maintenance reduces the risk of unplanned failure as well as the cost and time needed for repairs. A proactive approach which takes early action before symptoms are evident is recommended [9].

## CLEANING OPTIONS

In this context, "cleaning" stands for the removal of deposits within the generator winding and other components of the stator cooling water systems (e.g. strainers).

The types of deposits to be removed can mainly be divided into two categories:

- Foreign material: this includes paint chips, wires from steel brushes, dirt, gasket material, textiles, cigarette butts, insects, etc.

Diagnostic Method	Cleaning Recommended at	
	mid-term**	short-term**
	Any trend that indicates arriving at a specification limit*** within 12 months	2 months
Assessment of operating parameters	Events indicating a problem****	
Review of operating history	Events indicating a problem****	
Review of system water chemistry	Events indicating a problem****	
Strainer and filter clogging history	Increased frequency of clogging****	
Normalized pressure drop / flow, relative to original		
Pressure drop	> 20 %	> 40 %
Stator water flow	< 10 %	< 20 %
Individual bar * flow, relative to average within group	< 7.5 %	< 10 %
Normalized temperature on-line		
Water outlet temperature (rise above inlet)	> 10 %	> 20 %
Water outlet hose temperatures		
top bar * relative to top bar average	> 5 °C (9 °F)	> 7 °C (13 °F)
bottom bar * relative to bottom bar average	> 4 °C (7 °F)	> 6 °C (11 °F)
Stator slot * temperature relative to average of all slots	–	> 10 °C (18 °F)
Visual inspections		
Cooling water system components	Increased fouling****	
Stator bars	Visible deposits, but flow not yet restricted	Visible deposits, flow restricted
DC High-Potential Test	Suspicion of conductive deposits****	

Table 1:

Criteria for considering cleaning of the stator bars, in a typical water-cooled generator. The diagnostic methods refer to those listed and discussed in reference [3]. Action is recommended when one of these criteria has already been fulfilled. This table may be adapted to an individual generator's characteristics. However, there should be a substantiated reason for choosing different values and it should not be a way to legitimize a bad condition.

\* This item refers to one or more individual bars, hoses or slots that deviate from the rest within a group of comparable conditions.

\*\* Mid-term means action within 1 year and short-term means action within 2 months, and less if there is a faster trend in deterioration.

\*\*\* Do not trust the situation if it stabilizes without evident reason; "things that go away by themselves may come back by themselves".

\*\*\*\* Criteria will be plant-specific and subject to engineering judgment.

- Corrosion products of system materials: most prominent are the corrosion products of the copper hollow conductors
- CuO (cupric oxide)  
This oxide is predominant in high-oxygen water and is formed either during permanent high-oxygen conditions or during temporary oxygen excursions (incidents).
- Cu<sub>2</sub>O (cuprous oxide)  
This oxide is predominant in low-oxygen water. It transforms readily to CuO when the water is subjected to higher oxygen levels or another oxidizing substance (e.g. hydrogen peroxide).
- Cu (metallic copper)  
Deposits of small copper particles or even plated out copper are also sometimes found in generator cooling water systems.

The actual deposit in a hollow conductor is always a mix of these oxides. In low-oxygen plants, Cu<sub>2</sub>O is predominant, and in high-oxygen plants CuO. Metallic copper is usually only a minor component.

Deposits in generator cooling systems also comprise some iron oxides, even in the usual case where all steel in the system is of stainless grade. Quantities however are small and there is no known report of substantiated plugging. It is therefore considered that iron oxides do not merit the application of special techniques for their removal.

### Mechanical Cleaning

The cleaning effect is accomplished by the effect of mechanical force upon the matter to be removed. Typical tools include piano wires, drills, chisels, water jets and CO<sub>2</sub> blasting, for instance. Mechanical methods are – to a variable degree – effective on dirt and debris, as well as on deposited corrosion products. Drawbacks include limited access to the deposits – within a stator bar, only the inlet and outlet are typically accessible. The bar itself with the Roebel transposition can hardly be fully penetrated with a mechanical cleaning tool. If not performed care-

fully, the mechanical tool can scratch or even completely destroy the bar. Scratches on the copper surface have an increased surface area and roughness, and thus are prone to future crystal growth of copper oxides.

### Chemical Cleaning

The cleaning effect is accomplished by the effect of the chemicals dissolving the matter to be removed. The dissolved impurities can then be either drained or removed with an ion exchange bed.

Chemical methods can be directed specifically towards the matter to be dissolved. Usually chemical cleaning for generator cooling water systems is tailored to the removal of copper oxides. As will be explained later, the chemical removal of copper corrosion products requires oxidizing media.

### Limitations of Cleaning

- Hollow conductors that are completely blocked and do not have any water flow usually cannot be cleaned by any type of chemical cleaning. They require a preceding mechanical cleaning.
- With all the cleaning methods available, one important point should however be kept in mind: the cause of the plugging is not eliminated by the cleaning; reoccurrence of plugging cannot be excluded. Cleaning thus is not the final solution to the problem, but only removes the symptoms.

## METHODS FOR CLEANING OF HOLLOW CONDUCTORS

### Mechanical Cleaning

Mechanical cleaning is understood in this publication to be the removal of substances by means of a tool. Flushing is discussed separately.



Figure 1: Plant O3. Water box before (left) and after (middle) mechanical cleaning. Right: after subsequent complexant cleaning [10]. Note that all photos were taken from the same water chamber.

For mechanical cleaning, the hollow conductors must be accessed by the cleaning tool. Such a cleaning tool may be anything from a simple piece of stiff wire to a small robot. A practical device is a pre-bent guiding tube that funnels the wire into the hollow conductor. This guiding tube can be for example a small copper tube that is easily bent into the right shape, or a memory-shaped plastic tube that bends easily when warm but snaps into the desired shape when cooling down. This tube is directed either by direct vision or by videoscope.

This method may, at its best, cover the hollow conductor ends and some parts of the hollow conductor. The small cross section (typically on the order of 1.5 x 4 mm), the length (typically on the order of 5–10 m), and the twisted form at the Roebel transpositions hinder a deep penetration of cleaning tools into the hollow conductor.

It is evident that major disassembling is required for a mechanical cleaning. It can only be done with the generator shut down and the stator water connections disassembled.

An example is the case of Plant O3 (Figure 1). During a normal visual inspection at a planned outage, severely plugged hollow conductors were found. To prepare the machine for a global chemical cleaning, a mechanical cleaning was done with the water hoses removed and the water chamber and the hollow conductor ends directly accessible. A wire with a rounded tip was then pushed into the conductor to open up the completely blocked hollow conductors (Figure 1, left and middle). The two completely blocked hollow conductors on the bottom left were mechanically opened, but still had substantial deposits. Afterwards, a complexant cleaning was performed on the entire system. Post-inspection of the same waterbox (Figure 1, right) revealed that all copper oxides had been removed and full cooling efficiency was re-established.

Another example is the case of Plant PN3 (Figure 2). This stator had severely plugged hollow conductors. Assisted visual inspection identified 196 out of a total of 576 hollow conductors in the bottom bars as being completely plugged. Mechanical cleaning was done with the water hoses removed and the water chamber and the hollow conductor ends directly accessible. A stiff wire with a rounded tip (to prevent scratching) was then pushed into the conductor to remove the oxide plug. Subsequent individual conductor flow testing showed that all plugged conductors were opened and bar flow distribution improved considerably. However, for full restoration of flow, a subsequent chemical cleaning was necessary.

### Effect of Load Changes and Flow Changes

It has been observed that in generators with increased temperatures those temperatures sometimes improve when a temporary load reduction is carried out. A 20 % load reduction for half an hour may already be sufficient.

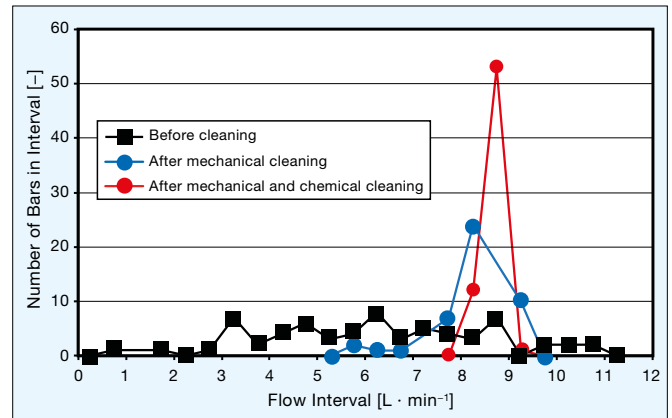


Figure 2: Plant PN3. Flow distribution in the stator bars before and after cleaning. The flow through each stator bar was measured on its outlet water hose by ultrasonic flow testing. Each bar was then related to the matching flow interval. The figure shows the number of bars in each interval. Before cleaning, the flow was severely impaired, and about 1/3 of all hollow conductors were completely plugged (black curve). Mechanical cleaning opened all hollow conductor passages and improved flow distribution of the individual bars considerably (blue curve). The final step towards normal flow distribution was then the following complexant cleaning (red curve).

A similar effect is sometimes observed when pressure shocks or sudden flow changes are made with the stator cooling water, e.g. by adding the standby pump. Such effects are also conceivable when changing the cooling water temperature.

Even though some improvement could be possible in individual cases, this is not recommended practice. These transients may produce unpredictable results. For example, more plugging could result due to the release of a crud burst that is caught in other plugged conductors. Cleaning effects are small and the technique does not provide a thorough cleaning. Additionally, there is also no way of controlling these processes, so they should not be a preferred option.

Such action may however be useful for saving a bad generator availability situation.

### Water Flushing, Air/Water Flushing

A sometimes useful technique to remove substances from the conductors is reversing the water flow. This especially liberates the conductor inlets from larger debris but is also capable of flaking off copper oxide deposits. Hard deposits that resist even mechanical cleaning tools (Figure 1, middle photo) can however rarely be removed by water flushing.

The installation required for reversing the flow varies from plant to plant. Some plants are already equipped with crossover pipes and valves permitting flow reversal with

no further installations. Most other plants however require temporary piping, which necessitates plant shutdown. It is important to provide fine filtration of the recirculating water in order to remove the substances from the system. Plants with stainless steel mesh filters or strainers should consider temporary 20-micron filter cloth inserts on the mesh.

Reverse flow flushing should be done with the maximum achievable flow. To be more effective, the coolers can be shut off to have the water temperature run up to around 50 °C. The duration of flushing depends on the nature and degree of plugging. In some cases, even after 5 days of hot reverse flushing there was still some debris being removed from the stator.

Figure 3 and Figure 4 give examples of the effects of reverse flow flushing in plant S3. In both cases considerable quantities of oxide sludge as well as other debris were removed by the hot reverse flow flushing (Figure 5). Water flow was quantified with ultrasonic flow measurements at the outlet water hose of each bar. The flow distribution of the individual bars showed some improvement, but it was not dramatic (Figure 3). This demonstrates that reverse flow flushing is good for doing "heavy duty cleaning", but is not sufficient to completely remove compact oxide plugging. To have all copper oxides in the system removed, it is crucial to also perform a chemical cleaning after the hot reverse flow flushing. The improvement in plant S3 can be seen in Figure 4.

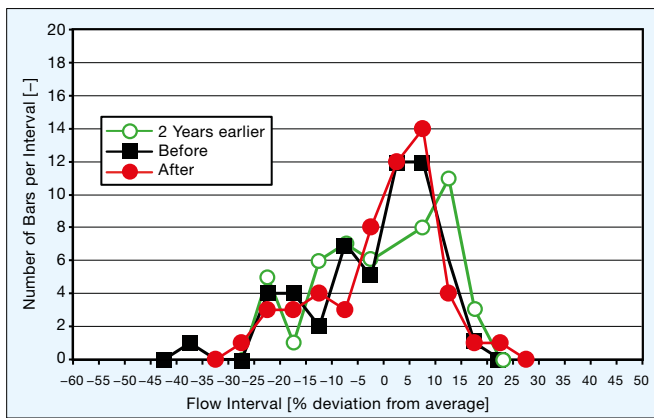


Figure 3: Plant S3. Bar water flow distribution after hot reverse flushing. It can be seen that bar flows had not changed much from the values obtained 2 years earlier (green and black curves). Hot reverse flow flushing did remove some deposits but did not significantly improve the flow distribution (black and red curves).

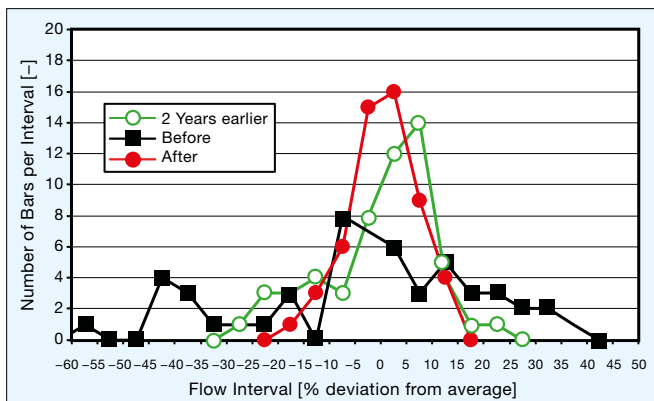


Figure 4: Plant S3. Bar water flow distribution after hot reverse flushing plus chemical cleaning. This is the same plant as in Figure 3, but at a later year. It can be seen that stator water flow had significantly deteriorated compared to 2 years earlier (green and black curves). Hot reverse flushing plus chemical cleaning improved the flow distribution significantly (black and red curves).

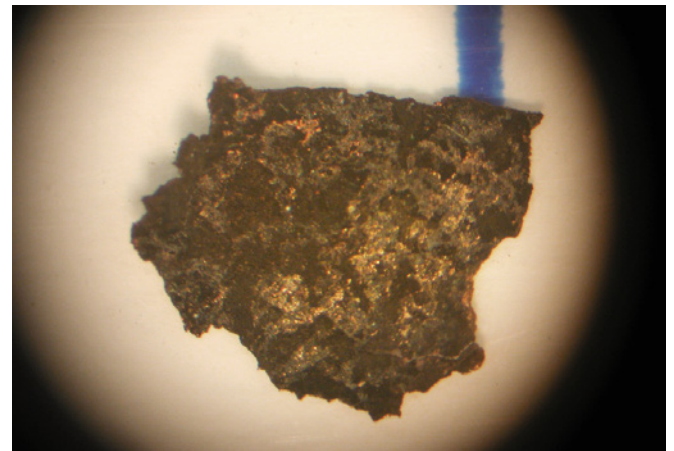


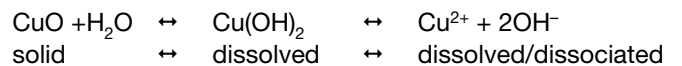
Figure 5: Plant S3. Oxide flake removed by hot reverse flow flushing (as in Figure 3). It is evident that the flushing has chipped off oxide flakes.

Another useful technique is to backflush individual bars with high-pressure air or a mixture of air and water droplets. When choosing the pressure, attention has to be given to the mechanical limits of the bar and its connections.

**Complexant Cleaning**

The mechanism of complexant cleaning is as follows [11]:

Copper oxides dissolve slowly in water until the equilibrium concentration is reached. The equation for the dissolution of CuO is:



The equilibrium concentration will be determined by the solubility product [12]. If a chelating agent (complexant) is added to the system, it will react with the Cu<sup>2+</sup> ion and thus remove it from the system, hence keeping the dissolution going.

It is important to note that the chelating agent does not dissolve the oxide. The oxide has to go into solution on

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its own. The chelant only removes the dissociated product and thus forces the continuous dissolution of the solid copper oxide. The chelant by itself does not dissolve or attack the solid substance.

The strength of the chelation is described by the stability constant. For instant,  $\text{Fe}^{3+}$ ,  $\text{Cu}^{2+}$  and  $\text{Fe}^{2+}$  make strongly bonded complexes with the chelant ethylene-diamine-tetraacetic acid (EDTA).

**Complexant cleaning can be done off-line as well as on-line** Differently from acids, complexants do not need a minimum strength for reacting with copper oxides. The chemical reaction is independent of the chemical concentration. Thus, the process can be done with a sufficiently dilute solution so it does not interfere with any conductivity limits. Complexant cleaning therefore can be done off-line as well as on-line, that is, with the generator in operation. However, special care and safeguards need to be in place to prevent a conductivity spike, which can trip the generator.

Due to the diluted solution, on-line chemical cleaning typically takes longer than off-line cleaning, on the order of 10–15 days. However, it does not interfere with plant operation.

**Choice of complexant** The choice has to make due consideration of the properties of copper and its oxides:

- CuO (cupric oxide)  
Cu<sup>2+</sup> forms a large number of complexes.
- Cu<sub>2</sub>O (cuprous oxide)  
Cu<sup>+</sup> also makes certain complexes, most notably with NH<sub>3</sub> and CN<sup>-</sup>. Other complexants that are active only on Cu<sup>2+</sup> may dissolve Cu<sub>2</sub>O with disproportionation into Cu<sup>2+</sup> ions and metallic copper. In such a case an oxidant is required to support cleaning.
- Cu (metallic copper)  
Metallic copper can be attacked by certain complexant mixes, even in the absence of oxidizing agents.

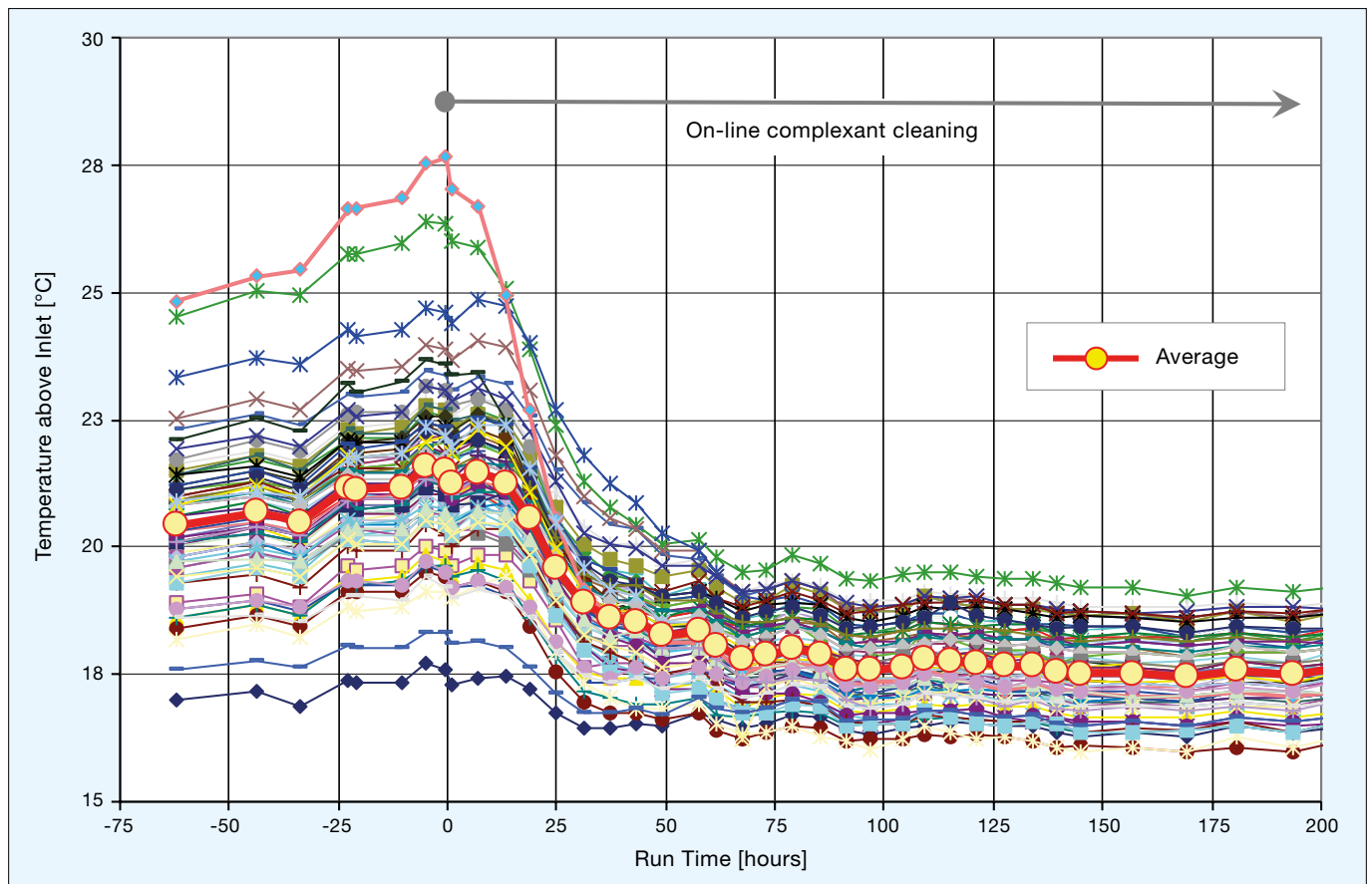


Figure 6: Plant P6. Improvement of stator slot temperatures by on-line complexant cleaning. All 72 stator slot temperatures were normalized to a constant reference load. Chemical cleaning started at zero hours run time. The improvement of the average temperature by 4 °C as well as the additional improvement (up to 10 °C) of the hotter bars can be seen. At the end of the cleaning, all slots were within the normal spread of temperatures.

A complexant is of practical use for cleaning only if the solubility of the reagent and the resulting copper compound in water is sufficiently large. The use of intermediate solubilization agents complicates process chemistry and may lead to secondary reactions.

Some complexing agents seem promising for CuO, others for Cu<sub>2</sub>O. A few of them even seem suitable for both but might come with the drawback of poor solubility in water.

The art of complexant cleaning consists of choosing the appropriate complexing agent together with the right balance of oxidant. Too much oxidizer may produce more oxides than the complexant can dissolve, while too little oxidizer makes the dissolution incomplete or may even leave conductive deposits on the isolating hoses. It has to be considered that some oxidizer is lost for cleaning by reactions other than those with deposits of copper and copper oxides, e.g. by the formation of oxygen gas that may vent off.

It is also important to consider its effect on all other involved materials and components. Especially the effect on the brazing material for the hollow conductors and the water boxes needs close attention. A thorough analysis

has recently been conducted [10]. Compared to acids, complexants are not particularly aggressive to system materials.

EDTA, like its readily water-soluble salt Na<sub>2</sub>H<sub>2</sub>-EDTA, is a long-time traditional cleaning agent for copper and has been used in a large number of generator cleanings.

**Application of complexant cleaning** Because of their relatively benign properties complexants are usually applied by recirculation in the generator cooling water system using the system recirculation pump.

The hollow conductors may have a bare surface after complexant cleaning. Depending on the water chemistry, re-establishment of a stable oxide layer may require a follow-up treatment. Without such reoxidation there may be a risk of rapid reoccurrence of the plugging (within a few weeks).

**Experiences** Complexant cleaning of generator cooling systems using EDTA has been successfully applied in more than 250 generator cleanings since 1980. If done properly, that is, with proper quantity and timing of the in-

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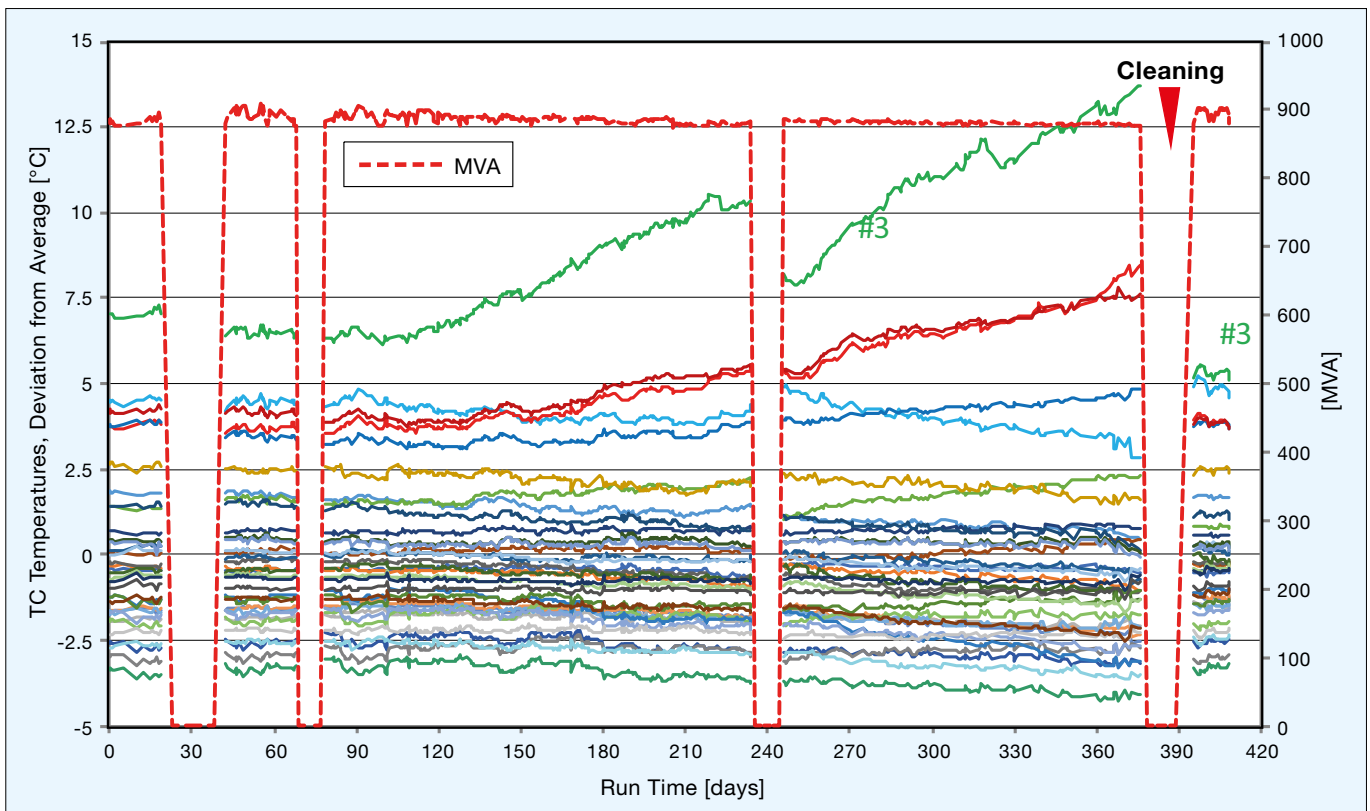


Figure 7: Plant O2: Outlet temperatures of the individual TC elements, before and after off-line complexant cleaning. The deterioration of flow before and the improvement after the cleaning can be seen. Temperatures were measured with TC elements at the outlet water hoses of each group of stator bars (one top bar in parallel with one bottom bar) and normalized to standard load (880 MVA). The dashed red curve (MVA) displays the actual generator load; the dips indicate periods where the plant was shut down.





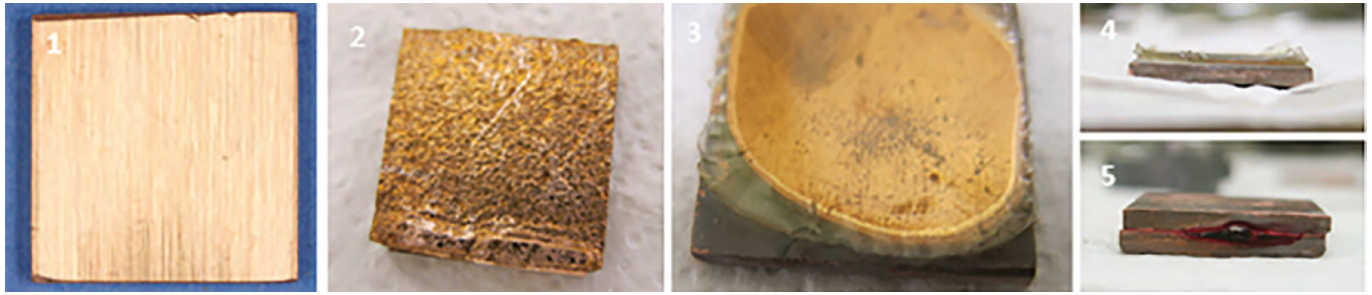


Figure 9:

Material tests in a mixed solution of phosphoric and sulphuric acid, together with hydrogen peroxide.

1: bare copper sample before acid treatment. 2–5: after acid treatment. 2: copper sample with brazing material; severe attack with cleaning. 3,4: epoxy coated sample to simulate a repair method; the coating detached with cleaning. 5: two copper plates bonded with cyanoacrylate to simulate a "super-glue" repair method; both the copper and the cyanoacrylate were attacked. Reprinted from reference [10].

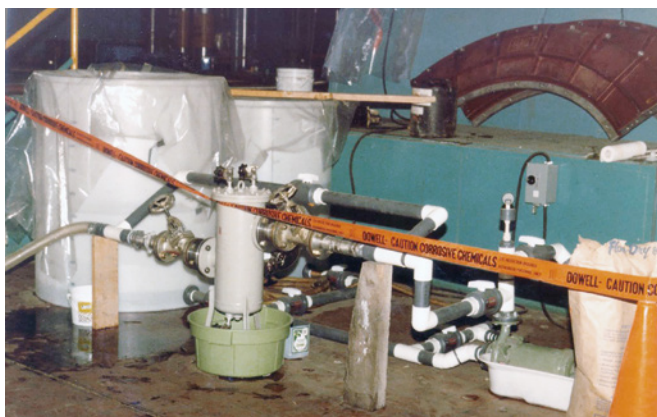


Figure 10:

Plant B2. Equipment for acid cleaning. The equipment is placed on the turbine floor, next to the opened generator.

- Cu (metallic copper)

Metallic copper is a relatively noble metal that is not dissolved by non-complexing solutions free of oxidizing agents [14]. Specifically, it is not soluble in acids like hydrochloric, sulphuric or phosphoric acid, but is soluble if an oxidizer (e.g. oxygen from air, hydrogen peroxide etc.) is present, or in oxidizing acids like nitric acid.

As with the use of chelants, when oxidizing acids or oxidizing acid solutions are used attention has to be given to an adequate balance between oxidizer and acid. Too much oxidation may produce more oxides than the acid can dissolve, while too little oxidation makes the dissolution incomplete or may even leave conductive deposits on the isolating hoses. It has to be considered that some oxidizer is lost for cleaning by reactions other than those with deposits of copper and copper oxides.

There are of course acids that have complexing properties; they do not necessarily require an oxidizer. Also, not only the acid, but also the more convenient salts may be used. Complexants were discussed earlier in this paper.

Sulphuric and phosphoric acids have been traditional agents for generator cleaning. Their effectiveness however is limited. Also considering the risk of plate-out of metallic copper, their use without any oxidizers cannot be recommended.

Citric acid and other organic acids like glycolic acid and gluconic acid have demonstrated their benefits. Their function is probably also related to complexing properties.

It is known that  $\text{NH}_4^+$  has strong complexing properties on Cu and on  $\text{Cu}^+$ . Ammonium salts of acids together with an oxidizer are therefore promising for the removal of generator deposits.  $(\text{NH}_4)_2\text{S}_2\text{O}_8$  (ammonium-peroxo-disulphate, or ammonium persulphate) is a substance that combines both these features.

When using an acid, it is also important to consider its effect on all other involved materials and components. Especially the effect on the brazing material for the hollow conductors and the water boxes needs close attention. This was analyzed in detail several years ago and a drastic effect on and removal of brazing materials by acids [10] was demonstrated; examples are shown in [Figure 9](#).

**Application of acid cleaning** The acid may be applied either by

- recirculation in the generator cooling water system with the system pump, or with a temporary pump; or
- application on disassembled bars, either individually or in groups.

Recirculation of acid in the system challenges all other system materials. The consequences of possible leaks also have to be considered. Leaks outside the generator may cause a safety hazard as the set-up of such a system is not designed for this kind of treatment. Leaks inside the generator may cause severe damage.

Acid flushing of disassembled bars avoids involvement of non-targeted components and facilitates risk management. However, major disassembly of the generator

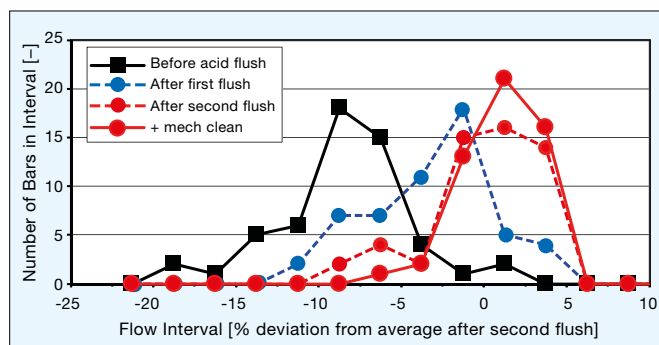


Figure 11: Plant B2. Flow distribution in the stator bars before and after acid cleaning.

is necessary, and it is not comfortable to have temporary plastic tubing carry acid to the inside of the stator housing.

Acid cleaning usually employs inhibitors to keep the attack on the hollow conductor material under control. They may however reduce the effectiveness of the cleaning.

As with complexant cleaning, the hollow conductors may have a bare surface after acid cleaning. Depending on the water chemistry, re-establishment of a stable oxide layer may require a follow-up treatment. Without such reoxidation there may be the risk of rapid reoccurrence of the plugging within few weeks.

**Experiences** Public reports on the experiences with acid cleaning of generators are rare. Good results have been achieved with ammonium-peroxo-disulphate and with citric acid [13].

Even with the use of inhibitors the quantity of copper removed from the stator by acid cleaning is on the order of 20–40 kg, which is much more than the oxide deposit, which is usually 2–5 kg. This means that substantial quantities of base metal are also dissolved.

Figure 10 and Figure 11 illustrate an acid cleaning of a 440 MW generator. Stator water flow had decreased from the normal value of  $1230 \text{ L} \cdot \text{min}^{-1}$  down to  $1003 \text{ L} \cdot \text{min}^{-1}$  and was subsequently brought back to  $1192 \text{ L} \cdot \text{min}^{-1}$  with this cleaning.

The stator was opened and the 108 stator bars were assembled into groups of up to 8 bars in parallel. Each group was then separately treated with acid in a special cleaning circuit (Figure 10). A solution based on ammonium-peroxo-disulphate together with hydrogen peroxide was applied at ambient temperature for 45 min in counterflow direction. After this acid treatment, the bars were rinsed down to low conductivity, and then flushed with air, at the same time measuring the air flow through each bar.

The air flow test showed that this cleaning did not produce a satisfactory result. A second acid flush of 75 min brought more improvement. Following this second acid flush the bars with the smallest flow were opened and mechanically cleaned (Figure 11). In those 20 bars, 10 out of the total of 160 hollow conductors were found to have still been plugged. Due to outage time constraints, further mechanical cleaning was not possible.

The cleaning removed 30 kg copper from the stator. A visual inspection showed that the copper surfaces had become rough, and the brazing had been pitted. Another 30 kg of copper were removed from the brass-tubed coolers.

The spent cleaning liquid was clear and had a green color. Within a few hours however it turned turbid and precipitation of red sludge took place (the main component was amorphous copper). This indicates that care must be taken that copper is not precipitated from the cleaning solution during some stage of the acid cleaning.

### Cationic Purification

This is a process developed by EdF (Electricité de France) and has been implemented in some of their nuclear power generators [16].

The generator cooling water is continually sprayed into the air space when entering the water tank. The mixed bed filter is temporarily replaced by a cation exchanger. The water thus is oxygen saturated and has a slightly acidic pH caused by carbon dioxide. Copper oxides and copper are slowly dissolved and subsequently removed by the cation exchanger.

Copper solubility changes along the path of water through the different parts of the system (e.g. solubility changes with temperature etc.). Therefore, attention has to be paid that the dissolved copper is not redeposited in the system before it is removed by the cation exchanger. This requires an exact knowledge of the local solubility as well as the deposition kinetics, which strongly depend on system design and operating parameters. Without such programming and close supervision there is a big risk that the cleaning may go wrong. The process also corrodes the bare metal, which can be excessive on sites with locally high turbulence (flow accelerated corrosion). Cationic purification was designed to be applied intermittently.

As the method has however been in limited use only, it will not be considered further.

### Follow-up Treatment after Chemical Cleaning

After thorough chemical cleaning, the copper surface is bare metal, which is stable in water and – differently from chemical cleaning of steel – does not require a passivation. If the water then contains oxygen, an oxide layer is formed again. Experience has shown that – depending on water chemistry – this oxide layer may however not always

Method	On-/Off-line		Benefit				Days Required		
	off-line	on-line	some	fair	good	excellent	< 5	5-15	> 15
Mechanical cleaning	x				x		x	x	
Load changes, flow changes		x	x				c		
Water flushing, water/air flushing	x			x			x		
Acid cleaning	x				x		x	x	
Complexant cleaning									
off-line	x				x		x		
on-line		x			x			c	
Mechanical cleaning combined with acid cleaning, complexant cleaning	x				x	x			x
Water flushing, water-/air flushing in combination with acid cleaning, complexant cleaning	x					x	x	x	

Table 2: Comparison of methods for removing flow restrictions. "On/off-line" specifies under which condition the method is available. "Benefit" is understood to be the degree of improvement normally achieved by the method. "Days required" indicates the time typically needed in 24/7 operation. c = a continuous process that does not interfere with generator operation.

be stable. It may dissolve, migrate and redeposit, thus plugging the generator within a short period. This can be avoided by applying a directed reoxidation.

Thus, in these cases, a controlled reoxidation might be useful [17]. The process can be optimized by the use of additives.

In contrast to high-oxygen systems, where reoxidation is a must, it is important to evaluate its usefulness on a case by case basis for low-oxygen machines. Under certain conditions, a controlled preoxidation might be useful and reduce the reoccurrence of plugging significantly.

### CHOICE OF THE METHOD

#### Comparison and Assessment of These Methods

Mechanical cleaning is able to locally remove severe and even complete plugging, but it does not provide a complete removal of deposits. Even if the method helps to reinstate a basic flow, the remaining deposits may still cause unsatisfactory flow and may be the nucleus for renewed deposition. Also, mechanical cleaning may require considerable effort for disassembling the stator bar connections.

Water flushing is relatively simple, but has only limited effectiveness. It will neither remove severe plugging nor provide a complete removal of deposit layers. There may

even be the risk that particles may get stuck more severely in the conductors than before.

Acid cleaning can be effective for severe and persistent plugging but is not effective on complete plugging. It attacks base material substantially. In order to minimize adverse effects on system materials and to permit better control, it should be performed by cleaning either individual bars or a small group of bars in parallel. This requires partial disassembly of the generator. The risk of acid leaking out of the system (especially onto the rotor) has to be taken into account. Acid cleaning is only possible off-line.

Complexant cleaning employs relatively benign reagents. Attack on base materials is very limited when it is done properly. Complexant cleaning works at small concentrations, so on-line cleaning (with the generator in operation) is possible if the necessary precautions are taken. Besides maintaining plant availability, on-line cleaning provides real-time monitoring of the cleaning effect, permitting immediate reaction if the process goes differently than expected. With off-line cleaning, many effects of cleaning are only seen at the subsequent restart. As smooth and easy as a complexant cleaning sounds, it needs expert supervision to use the right chemicals, oxidizing agents and additives at the correct time with the correct concentration. Otherwise severe damage to the generator might be the outcome.

Hollow conductors that are completely blocked and do not have any water flow usually cannot be cleaned by any type of chemical cleaning. They require a preceding mechanical cleaning.

The most efficient method to remove deposits is the combination of mechanical with chemical cleaning.

This assessment is summarized in [Table 2](#).

### Recommendations

The first step is a diagnosis of the cooling conditions of the generator. Proactive monitoring gives reliable trends in long-term performance and may already indicate the nature and intensity of plugging.

If the generator is heavily fouled, mechanical cleaning should be considered. This especially applies if some hollow conductors are completely plugged. Mechanical cleaning should be followed up by a complexant cleaning.

If the generator is not heavily fouled, water or water/air flushing or complexant cleaning can be applied.

Water flushing may be an easy first try for the removal of plugging. Expectations should however not be too high. Also, when there is no visible success, flushing should be terminated in order not to solidify deposits more than they already are.

Complexant cleaning is the recommended option. It is possible off-line as well as on-line. On-line cleaning does not interfere with generator availability, and also provides real-time monitoring of the cleaning effects. However, on-line cleaning takes some time (usually 10–15 days) and is expensive.

### OPERATING THE GENERATOR AFTER CLEANING

The cause of the plugging is typically not eliminated by cleaning; reoccurrence of plugging cannot be excluded. Cleaning thus is not the final solution to the problem and only removes the symptoms.

Besides searching for and controlling the root cause of plugging, it is recommended to review and upgrade the operating practices of the system. This includes:

- Redefining chemistry and operating parameters
- Optimizing system equipment, instrumentation and parameters to maintain cleanliness
- Optimizing monitoring equipment and practice
- Optimizing outage lay-up practice
- Providing adequate training and management information

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### REFERENCES

- [1] Svoboda, R., Blecken, W. D., "Corrosion and Deposits in Water-Cooled Generator Stator Windings: Overview of Water Cooling of Generators", *PowerPlant Chemistry* **2018**, 20(5), 290.
- [2] Svoboda, R., "Corrosion and Deposits in Water-Cooled Generator Stator Windings, Part 1: Behaviour of Copper", *PowerPlant Chemistry* **2018**, 20(5), 297.
- [3] Svoboda, R., Chetwynd, R., "Corrosion and Deposits in Water-Cooled Generator Stator Windings, Part 2: Detection of Flow Restrictions", *PowerPlant Chemistry* **2018**, 20(6), 326.
- [4] Bauer, T., Svoboda, M., Svoboda, R., "Corrosion and Deposits in Water-Cooled Generator Stator Windings, Part 3: Removal of Flow Restrictions", *PowerPlant Chemistry* **2019**, 21(1), 8, this article.
- [5] Bauer, T., Svoboda, M., "Corrosion and Deposits in Water-Cooled Generator Stator Windings, Part 4: Operating Experience with Flow Restrictions in Stator Cooling Water Systems", *PowerPlant Chemistry* **2019**, 21(2), to be published.
- [6] *Turbine Generator Auxiliary System Maintenance Guide Volume 4: Generator Stator Cooling Water System: 2013 Update*, **2013**. Electric Power Research Institute, Palo Alto, CA, USA, EPRI 3002000420.
- [7] *Guidelines for Detecting and Removing Flow Restrictions of Water-Cooled Stator Windings*, **2002**. Electric Power Research Institute, Palo Alto, CA, USA, EPRI 1004704.
- [8] Seipp, H.-G., "Betriebserfahrungen mit wassergekühlten Generatorwicklungen", *VGB Kraftwerkstechnik* **1983**, 63(5), 408.
- [9] Chetwynd, R., Sarette, T., Svoboda, R., "A Pro-Active Approach towards Maintaining the Integrity of Large Electric Generator Water-Cooled Windings", *Proc., 5th SFEN Conference on Contribution of Materials Investigation to the Resolution of Problems Encountered in Pressurized Water Reactors*, **2002** (Fontevraud, France) Société Française d'Énergie Nucléaire, Paris, France.

- [10] Bauer, T., Svoboda, M., Dockheer, S., Svoboda, R., "Chemical Cleaning of Water-Cooled Generators: Effect on System Materials", *PowerPlant Chemistry* **2014**, 16(2), 94.
- [11] *Guidelines for Chemical Cleaning of Conventional Fossil Plant Equipment*, **2001**. Electric Power Research Institute, Palo Alto, CA, USA, EPRI 1003994.
- [12] Svoboda, R., Palmer, D. A., "Behaviour of Copper in Generator Stator Cooling-Water Systems", *presented at the 15th International Conference on the Properties of Water and Steam*, **2008** (Berlin, Germany). International Association for the Properties of Water and Steam. Also published in: *PowerPlant Chemistry* **2009**, 11(2), 70.
- [13] Nasri, L., Leinonen, P., Puzzuoli, F. V., Swami, D., "Ontario Power Generation Operational Experience with Stator Conductor Bars Fouling", *PowerPlant Chemistry* **2003**, 5(3), 155.
- [14] Pourbaix, M., *Atlas of Electrochemical Equilibria in Aqueous Solutions*, **1966**. Pergamon Press, Oxford, UK, ISBN 978-0915567980.
- [15] Pascal, P., *Nouveau Traité de Chimie Minérale*, **1957**. Masson & Cie., Paris, France.
- [16] Drommi, J.-L., Mesnage, F., "How to Prevent Hollow Conductor Plugging: EdF Solution for Aerated Systems", *PowerPlant Chemistry* **2003**, 5(4), 203.
- [17] Svoboda, R., Sandmann, H., Seipp, H.-G., Liehr, C., "Water Chemistry in Generator Water Cooling Systems", *Proc., Interaction of Non-Iron-Based Materials with Water and Steam 1996 (Eds. R. B. Dooley and A. Bursik)*, **1997** (Piacenza, Italy). Electric Power Research Institute, Palo Alto, CA, USA, EPRI TR-108236.

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