

LOW-CONDUCTIVITY WATER SYSTEMS FOR ACCELERATORS*

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Abstract

The performance of low-conductivity water (LCW) systems is of critical importance at accelerator facilities. An imbalance of water chemistry, supply temperature, or component availability can have a direct impact on machine performance. Downtime of the LCW system for any reason can result in downtime of the entire accelerator. LCW systems for copper components are similar to stator cooling systems for electric power generating equipment with respect to the chemistry of soluble copper and resultant corrosion. The basics of copper corrosion and agglomeration mechanisms, impact of dissolved oxygen concentration and pH, copper solubility data and its relationship with temperature, and relative corrosion rates for various possible operating regimes are available from existing literature and will be reviewed. Water treatment for aluminum LCW systems is different than for copper systems and will be outlined. Fundamental features of control systems capable of controlling LCW temperatures within a fraction of a degree will also be discussed. Operational reliability is very much related to system design, component selection, and operating practices, and some anecdotal information will be offered based on the author's experience.

INTRODUCTION

Accelerator components made of copper are routinely cooled by deionized (DI), low-conductivity water (LCW). Release of copper oxides from parent surfaces is common. Releases comprise reddish-brown residue (Cu_2O) and, depending on the concentration of dissolved oxygen (DO), black residue (CuO). Copper oxide scale can be released and can agglomerate such that flow through system components is significantly restricted or blocked altogether [1].

Water treatment considerations for aluminum systems are quite different than for copper systems. This discussion will be based on the experience at the Advanced Photon Source (APS) where aluminum LCW systems are segregated from copper LCW systems.

Components such as accelerating structures and radio frequency (rf) cavities routinely require temperature conditioning to tolerances in the neighborhood of ± 0.05 - 0.1°C [2]. Conditioning is commonly performed with the LCW system. Such tolerances can be maintained using commercially available fluid-handling equipment and instrumentation, provided certain design parameters and techniques are employed.

Operational reliability is a strong function of system design and component selection. Certain design and

implementation practices result in tangible benefits to the accelerator operator in the form of reduced downtime and reduced durations of repairs if downtime occurs.

COPPER CHEMISTRY

From the point of view of copper chemistry, accelerator LCW systems can be compared to stator cooling systems in electric power plants. Like copper accelerator components, copper stators in power generation equipment are cooled using LCW and are subject to the effects of copper corrosion and subsequent agglomeration and plugging. Plugging is exacerbated by high heat flux across copper surfaces since copper solubility is reduced as water temperature rises. The information presented here is assembled from the existing literature in the power industry and from conversations with experts [3-10].

Corrosion Mechanism [11]

Oxygen (O_2) and carbon dioxide (CO_2) are present in water due to interactions with the atmosphere. An oxide forms at the metal surface, which, in the absence of other influences, is stable. The presence of CO_2 in the water results in the formation of carbonic acid (H_2CO_3), which dissociates into HCO_3^- and hydrogen ions (H^+). H^+ , which has an affinity for the oxygen atoms of the oxide, readily reacts to form water. The copper at the surface is now left in its ionic form and readily dissolves. The metal surface, now unprotected by the oxide, is again exposed to water, DO, and H^+ , allowing the process to recur.

Dissolved Oxygen Concentration

The corrosion rate of copper in water (at neutral pH) as a function of DO is indicated in Fig. 1 [12]. The maximum rate occurs in the range of 200-300 ppb. "Low oxygen" and "high oxygen" operating regimes are defined relative to this maximum. Corrosion in low-oxygen regimes

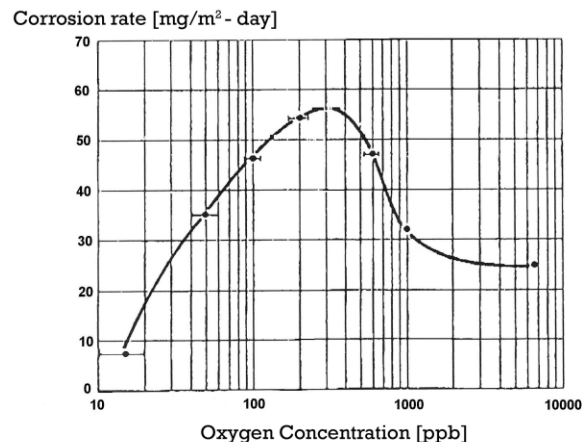


Figure 1: Corrosion rate vs. DO.

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occurs mostly as Cu_2O . Corrosion in high-oxygen regimes occurs mostly as CuO . Copper cooling systems can be operated successfully in either regime. For high-oxygen systems, oxygen content must be actively maintained as, without the deliberate introduction of oxygen, DO will fall naturally as a result of the corrosion process. In the case of stator cooling systems, the choice is usually specified by the manufacturer but is sometimes changed by the owner if operating experience indicates a benefit [10,13].

Influence of pH

H^+ concentration influences the corrosion rate, as indicated in Fig. 2 [12]. The rate is minimized at pH values approaching 8.5 and greater. The Pourbaix diagram in Fig. 3 [14] indicates stable forms of copper in aqueous solution as a function of pH and metal potential. For pH values below 7.0, the copper ion is stable in solution. Formation of the ion occurs from the oxide state when pH is just below 7.0. Reaction of H^+ with the oxygen of the oxide occurs readily under these conditions.

For pH values above 7.0, the preferred form of the metal is the oxide. Replacement of the oxygen in the oxide does not occur as easily and slows the corrosion mechanism. This is consistent with Fig. 2 and provides an understanding of reduced corrosion rates when the solution is alkaline.

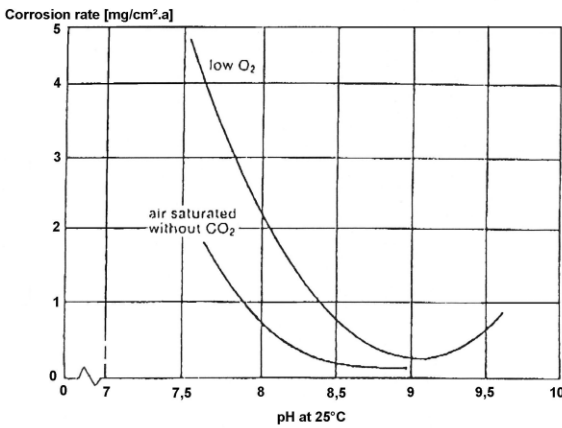


Figure 2: Corrosion rate vs. pH.

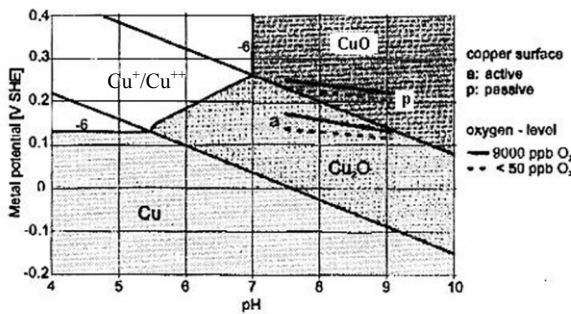


Figure 3: Pourbaix diagram for copper.

Influence of Temperature

Temperature plays a significant role in the solubility of copper in water, particularly at neutral to acidic pH. Figure 4 [13,15] indicates the relationship of copper solubility as a function of temperature for various values of pH. Figure 5 [13,15] indicates the relationship of solubility in terms of pH for various temperatures. When pH is lower than 7.0, the influence of temperature is more noticeable and provides an explanation for water flow restrictions that occur at the outlet ends of copper components where heat transfer takes place along the length of the component. It is logical to assume that most accelerator LCW systems operate under these constraints.

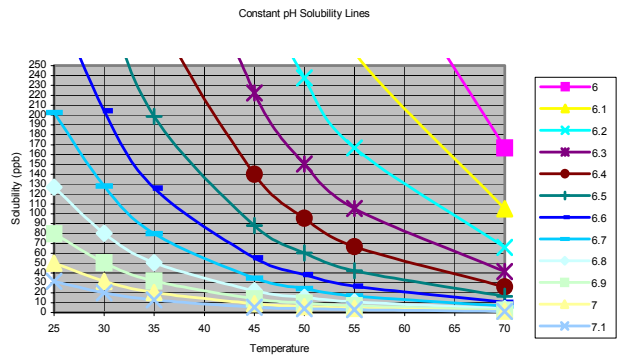


Figure 4: Copper solubility vs. temperature.

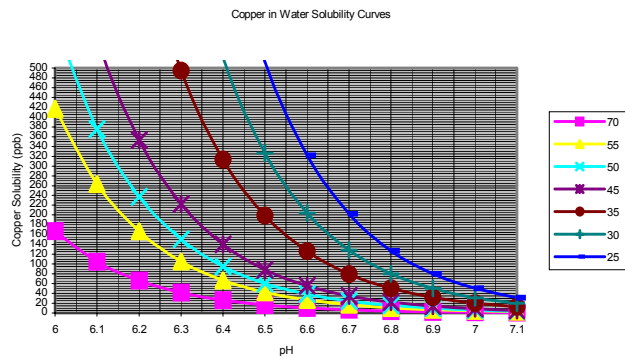


Figure 5: Copper solubility vs. pH.

Operating Regimes

Several options exist for choosing an operating regime for a copper-water system. These are:

- Neutral pH, low oxygen,
- Neutral pH, high oxygen,
- Elevated pH, low oxygen, and
- Elevated pH, high oxygen.

Figure 6 shows corrosion rate data for various operating regimes [13].

Limitations on Operating Regimes

The relationship between pH and resistivity of DI water is shown in Fig. 7. Most resins have a cation component in the hydrogen form and produce DI water to the left side of the curve ($\text{pH} < 7$). If cation is in the sodium form, DI water is produced to the right side of the curve ($\text{pH} > 7$).

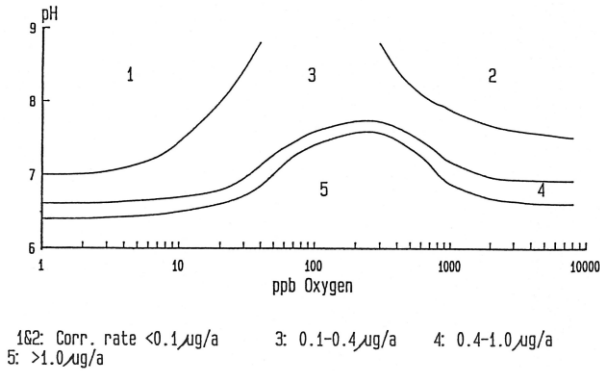


Figure 6: Corrosion data at various operating regimes.

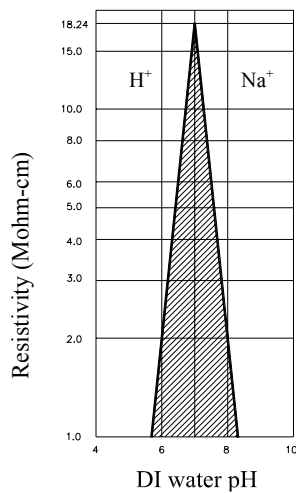


Figure 7: Resistivity limits of DI water.

Operation of a water system at a pH of 8.5 would require a resistivity of 1 Mohm-cm or lower. For many accelerators, this is not acceptable [1]. For example, at the APS, a resistivity value below 3.0 is not acceptable from the point of view of leakage currents. A more realistic minimum for resistivity is around 5.0. The corresponding maximum pH that is feasible is about 7.5.

With the maximum pH of an accelerator LCW system limited to 7.5 (essentially neutral), it is clear that the low-oxygen operating regime is more desirable since corrosion rates can be reduced to a lower value than for high oxygen (see Fig. 6).

Means of Controlling pH

It is common for resistivity to be maintained in LCW systems by the use of ion exchange resins. Positively charged ions are typically removed from the system by the cation resin and replaced with hydrogen ions. When this process occurs, the hydrogen ion content of the water system is increased (i.e., pH decreases). If the cation resin is processed in the sodium form, however, positively charged ions are replaced with a sodium ion, and the pH value increases.

Such a means is being employed in a stator cooling system at an Eskom generating facility in South Africa [13]. The treatment stream can be passed through either of two mixed-bed resin tanks as indicated in Fig. 8. When pH falls to a low limit, the mixed-bed tank with cation resin in the sodium form is brought online while the mixed bed in the hydrogen form is isolated (pH will rise). When pH again rises to a high limit, the mixed-bed tank with cation resin in the hydrogen form is brought online while the mixed bed in the sodium form is isolated (pH will fall).

Although pH control is achieved, the sampled process variable is resistivity (or conductivity) because of the direct relationship between resistivity and pH (see Fig. 7). It is important to verify periodically by direct pH measurement that the system exists on the positively sloped portion of the pH-resistivity curve (Fig. 7).

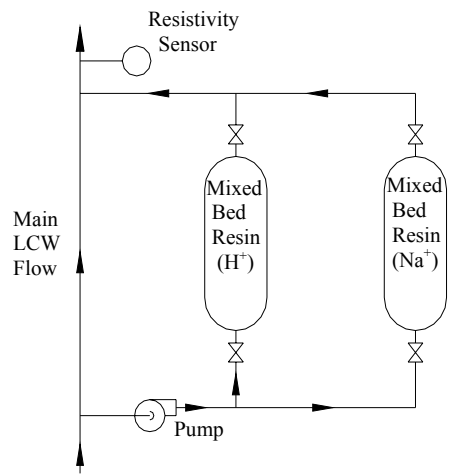


Figure 8: pH control method with mixed-bed resins.

Dealing with Copper Corrosion

Since copper corrosion can be minimized but not prevented altogether, it is necessary to be aware of techniques that will prevent or reduce the possibility of plugging. Experience at the APS indicates there are benefits to employing some of the following practices [1].

The use of small (<1/8" diam.) orifices for regulation of water flowrate should be avoided. This includes the use of passive flow-control devices having small, variable-area openings. Experience indicates that such orifices eventually experience build-up of copper oxide scale that reduces (or even stops) flow. At APS, such orifices and flow regulators are being replaced successfully with lengths of small-diameter tubing (e.g., 1/4" and 5/16" diam.). Such tubing is usually coiled for convenience.

Point-of-use filtration to around 0.5 micron nominal (2 micron absolute) has been successful. Filters are replaced only when differential pressure indicates a build-up. Changing filters on a routine schedule is avoided because it allows the ingress of oxygen and promotes higher corrosion rates.

All LCW that is treated in the central treatment loop is filtered to 0.05 micron. The treatment rate is approximately 5% of the total system throughput.

All make-up water is introduced to the LCW system at a vacuum deaerator to remove all but trace DO.

Branch lines that are not used regularly are maintained with a continuous minimum flow. A branch line with no flow can be a place where DO accumulates when the system is opened for maintenance. If not flushed with low-oxygen water, the branch will be a continuous source of DO contamination where it connects to rest of the LCW system.

Pump seals are flushed from the stuffing box out to the pump suction to avoid direct impingement of copper particles on seal faces. This avoids the build-up of copper oxides on seal faces, which was observed after numerous failures.

The use of flow-measuring equipment with moving parts is avoided. These moving parts are eventually coated with copper oxide. Moving parts are likely to fail in time.

It is imperative that the source of water for the initial system fill and for make-up be free of biological contamination. Once the system is filled, water must be kept circulating continuously to avoid stagnation and the possible growth of bacteria, as microbiologically influenced corrosion (MIC) can occur. A further precaution that may be taken is the use of ultraviolet (UV) radiation treatment of the polishing stream. The UV radiation interferes with the reproductive process of any microbes. Operation at trace DO levels further gives aerobic biological constituents (the first bacteria to collect in a colony) little oxygen to survive.

ALUMINUM LCW SYSTEMS

The information presented in this section is based on the implementation of aluminum LCW systems at the APS where aluminum accelerator components are conditioned by independent water loops operating at approximately 25°C containing no copper. This decision was taken to avoid a conflict in the needs between aluminum LCW treatment and treatment for copper LCW. As a result, electrochemical exchange of ions between copper and aluminum components is prevented.

Aluminum surfaces in LCW systems benefit from the very stable oxide layer that forms naturally, especially during initial operation. It is desirable to clean inside surfaces by a mild acid flush (such as an environmentally friendly, citric-based detergent) or by electropolishing. Upon initial fill with DI water containing naturally occurring levels of oxygen, heating the water to as high as 130-150°C will cause the deposition of a protective oxide layer to passivate inside surfaces.

Water treatment needs include only the polishing of the system with mixed-bed resins in the standard hydrogen form. Systems at APS operate between 13-16 Mohm-cm.

These systems are occasionally used to condition the APS vacuum chambers at 130-150 °C (“bakeout”) prior to

operation at ultrahigh vacuum. During this process, the water in the system is maintained in a low-conductivity condition by purging DI water (13-15 Mohm-cm) from a cooling loop into the heated bakeout loop at a rate of around 10% of the total bakeout flowrate. Water is simultaneously removed from the bakeout loop at an equivalent rate with the use of a heat recovery exchanger to minimize the heat load on the clean water purge. In this manner, mixed-bed resins are not exposed to bakeout system temperatures

TEMPERATURE REGULATION

Regardless of the tolerance of a temperature control system, traditional regulation systems employ feedback loops known as proportional-integral-derivative (PID) systems to control temperature. These systems have a sensor to detect the temperature and a controller to compare the actual temperature to a desired set point. The controller computes and delivers an output signal to a valve that throttles LCW flow through a heat exchanger. A system that has been successful at the APS is shown in Figure 9.

The detection of the actual LCW temperature is critical to maintaining regulation within tolerance. It is imperative that the resolution of the temperature-detection system be at least an order of magnitude better than the desired temperature tolerance. For example, if a tolerance of ±0.1°C is desired, it is necessary to detect changes in temperature on the order of 0.01°C or smaller.

The resolution of the temperature detection portion of the loop is determined by the incremental steps corresponding to the output of the analog-digital (A-D) converter in the processor. For example, if a temperature transmitter with a range of 50 °C is employed with a 16-bit A-D converter, the resolution will be $50/2^{15} = 0.0015$ °C (one bit is used for the sign of the number).

Throttle control valves must be matched to the application such that the smallest incremental change of valve position results in a temperature change less than the desired tolerance. Valves with actuators/positioners having a resolution of 0.25 to 0.5% have been used successfully.

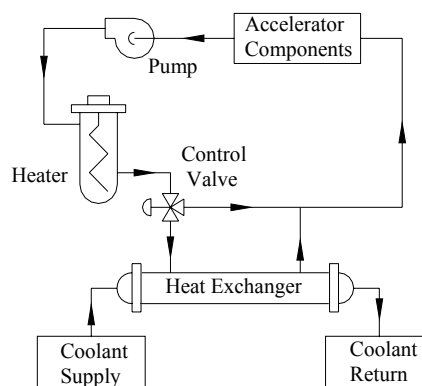


Figure 9: Temperature control loop employing mixing.

The choice of valve style is equally critical. The valve must have a dynamic range that is useful over a wide range of valve positions. One choice that has been employed successfully is a characterized three-way rotating plug valve. If a single valve or combination of two valves is used, a V-ball or characterized seat ball valve is recommended. Such valves can have a dynamic range on the order of 100:1.

It is essential that operating personnel responsible for system performance understand the process of control valve tuning to provide for the proper response of the valve to process upsets. For steady-state temperature control systems, the derivative term is usually not employed. Classes and texts to learn methods for control valve tuning are available from a range of sources [16].

Successful implementation of temperature control systems requires that time delays between temperature detection and valve actuation be minimized. It is imperative that the temperature sensor itself have a short time constant (e.g., 4 s) and be immersed directly in the water stream. The sensor should be located as near to the control valve as possible, and the valve should be located as near to the heat exchanger as possible.

Response times can also be reduced by implementing a system that employs mixing of relatively warm and cool streams to affect the delivery temperature as shown in Figure 9. If the mixing type system is replaced by a system that throttles coolant flow, changes in delivered water temperature require changes of the entire exchanger temperature rather than that of the delivered water only. This results in greater thermal inertia.

Accelerator components may not provide sufficient heating of LCW to allow for mixing of streams that are matched to the control valve and heat exchanger. In this case, it may be necessary to provide an additional heat source.

RELIABILITY

Operational reliability can be improved by following practices that have proven their value:

- Combine elements having similar flow rates into common series flow circuits to reduce the number of flow elements and related instrumentation.
- Remove flow-related instruments from all secured enclosures to reduce the time required to make repairs and exposure to radiation.
- Avoid flow elements with moving parts. Obstruction-type flow elements are an excellent alternative.

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