

WATER TREATMENT

<i>Water Characteristics</i>	48.1
<i>Corrosion Control</i>	48.2
<i>Scale Control</i>	48.4
<i>Biological Growth Control</i>	48.5

<i>Suspended Solids and Deposition Control</i>	48.7
<i>Start-Up and Shutdown of Cooling Tower Systems</i>	48.8
<i>Selection of Water Treatment</i>	48.9
<i>Terminology</i>	48.11

THIS chapter covers the fundamentals of water treatment and some of the common problems associated with water in heating and air-conditioning equipment.

WATER CHARACTERISTICS

Chemical Characteristics

When rain falls, it dissolves carbon dioxide and oxygen in the atmosphere. The carbon dioxide mixes with the water to form carbonic acid (H_2CO_3). When carbonic acid contacts soil that contains limestone (CaCO_3), it dissolves the calcium to form calcium carbonate. Calcium carbonate in water used in heating or air-conditioning applications can eventually become scale, which can increase energy costs, maintenance time, equipment shutdowns, and could eventually lead to equipment replacement.

The following paragraphs discuss typical chemical and physical properties of water used for HVAC applications.

Alkalinity is a measure of the capacity to neutralize strong acids. In natural waters, the alkalinity almost always consists of bicarbonate, although some carbonate may also be present. Borate, hydroxide, phosphate, and other constituents, if present, are included in the alkalinity measurement in treated waters. Alkalinity also contributes to scale formation.

Alkalinity is measured using two different end-point indicators. The **phenolphthalein alkalinity** (P alkalinity) measures the strong alkali present; the **methyl orange alkalinity** (M alkalinity), or **total alkalinity**, measures the total alkalinity in the water. Note that the total alkalinity includes the phenolphthalein alkalinity. For most natural waters, in which the concentration of phosphates, borates, and other noncarbonated alkaline materials is small, the actual chemical species present can be estimated from the two alkalinity measurements (Table 1).

Alkalinity or acidity is often confused with pH. Such confusion may be avoided by keeping in mind that the pH is a measure of hydrogen ion concentration expressed as the logarithm of its reciprocal.

Chlorides have no effect on scale formation but do contribute to corrosion because of their conductivity and because the small size of the chloride ion permits the continuous flow of corrosion current when surface films are porous. The amount of chlorides in the water is a useful measuring tool in evaporative systems. Virtually all other constituents in the water increase or decrease when common treatment chemicals are added or because of chemical changes that take place in normal operation. With few exceptions, only evaporation affects chloride concentration, so the ratio of chlorides in a water sample from an operating system to those of the makeup water provides a measure of how much the water has been concentrated. (Note: Chloride levels will change if the system is continuously chlorinated.)

Dissolved solids consist of salts and other materials that combine with water as a solution. They can affect the formation of cor-

Table 1 Alkalinity Interpretation for Waters^a

If	Then, Carbonate	Bicarbonate	Free CO_2
P Alk = 0	0	M Alk	Present
P Alk < 0.5M Alk	2P Alk	M Alk – 2P Alk	0
P Alk = 0.5M Alk	2P Alk = M Alk	0	0
P Alk > 0.5M Alk ^b	2(M Alk – P Alk)	0	0

^a P Alk = Phenolphthalein alkalinity. M Alk = Methyl orange (total) alkalinity.

^b Treated waters only. Hydroxide also present.

rosion and scale. Low-solids waters are generally corrosive because they have less tendency to deposit protective scale. If a high-solids water is nonscaling, it tends to produce more intensive corrosion because of its high conductivity. Dissolved solids are often referred to as total dissolved solids (TDS).

Conductivity or **specific conductance** measures the ability of a water to conduct electricity. Conductivity increases with the total dissolved solids. Specific conductance can be used to estimate total dissolved solids.

Silica can form particularly hard-to-remove deposits if allowed to concentrate. Fortunately, silicate deposition is less likely than other deposits.

Soluble iron in water can originate from metal corrosion in water systems or as a contaminant in the makeup water supply. The iron can form heat-insulating deposits by precipitation as iron hydroxide or iron phosphate (if a phosphate-based water treatment product is used or if phosphate is present in the makeup water).

Sulfates also contribute to scale formation in high-calcium waters. Calcium sulfate scale, however, forms only at much higher concentrations than the more common calcium carbonate scale. High sulfates also contribute to increased corrosion because of their high conductivity.

Suspended solids include both organic and inorganic solids suspended in water (particularly unpurified water from surface sources or those that have been circulating in open equipment). Organic matter in surface supplies may be colloidal. Naturally occurring compounds such as lignins and tannins are often colloidal. At high velocities, hard suspended particles can abrade equipment. Settled suspended matter of all types can contribute to concentration cell corrosion.

Turbidity can be interpreted as a lack of clearness or brilliance in a water. It should not be confused with color. A water may be dark in color but still clear and not turbid. Turbidity is due to suspended matter in a finely divided state. Clay, silt, organic matter, microscopic organisms, and similar materials are contributing causes of turbidity. Although suspended matter and turbidity are closely related they are not synonymous. Suspended matter is the quantity of material in a water that can be removed by filtration. The turbidity of water used in HVAC systems should be as low as possible. This is particularly true of boiler feedwater. The turbidity can concentrate in the boiler and may settle out as sludge or mud and lead to deposition. It can also cause increased boiler blowdown, plugging, overheating, priming, and foaming.

The preparation of this chapter is assigned to TC 3.6, Water Treatment.

Biological Characteristics

Bacteria, algae, and fungi can be present in water systems, and their growth can cause operating, maintenance, and health problems. Microorganism growth is affected by temperature, food sources, and water availability. Biological growth can occur in most water systems below 65°C. Problems caused by biological materials range from green algae growth in cooling towers to slime formation from bacteria in secluded and dark areas. The result can be plugging of equipment where flow is essential. Dead algae are often characterized by foul odors and mud-like deposits, which are often high in silica from the cell walls of the diatoms. These problems can be eliminated, or at least reduced to reasonable levels, by mechanical or chemical treatment.

CORROSION CONTROL

Corrosion is the destruction of a metal or alloy by chemical or electrochemical reaction with its environment. In most instances, this reaction is electrochemical in nature, much like that in an electric battery. For corrosion to occur, a corrosion cell consisting of an anode, a cathode, an electrolyte, and an electrical connection must exist. Metal ions dissolve into the electrolyte (water) at the anode. Electrically charged particles (electrons) are left behind. These electrons flow through the metal to other points (cathodes) where electron-consuming reactions occur. The result of this activity is the loss of metal and often the formation of a deposit.

Types of Corrosion

Corrosion can often be characterized as general, localized or pitting, galvanic, caustic cracking, corrosion fatigue, erosion corrosion, and microbiological corrosion.

General corrosion is uniformly distributed over the metal surface. The considerable amount of iron oxide produced by generalized corrosion contributes to fouling.

Localized or pitting corrosion exists when only small areas of the metal corrode. Pitting is the most serious form of corrosion because the action is concentrated in a small area. Pitting may perforate the metal in a short time.

Galvanic corrosion can occur when two different metals are in contact. The more active (less noble) metal corrodes rapidly. Common examples of galvanic corrosion in water systems are steel and brass, aluminum and steel, zinc and steel, and zinc and brass. If galvanic corrosion occurs, the metal named first corrodes.

Corrosion fatigue may occur by one of two mechanisms. In the first mechanism, cyclic stresses (for example, those created by rapid heating and cooling) are concentrated at points where corrosion has roughened or pitted the metal surface. In the second type, cracks often originate where metal surfaces are covered by a dense protective oxide film, and cracking occurs from the action of applied cyclic stresses.

Caustic cracking occurs when metal is stressed, water has a high caustic content, a trace of silica is present, and a mechanism of concentration occurs.

Stress corrosion cracking can occur in alloys exposed to a characteristic corrosive environment and subject to tensile stress. The stress may be either applied, residual (from processing), or a combination. The resulting crack formation is generally intergranular.

Erosion corrosion occurs as a result of flow or impact that physically removes the protective metal oxide surface. This type of corrosion usually takes place due to altered flow patterns or a flow rate that is above design.

Microbiologically influenced corrosion occurs when bacteria secrete corrosive acids on the metal surface. Often bacteria commingle with dirt and silt that protect the bacteria from biocides.

Factors That Contribute to Corrosion

Moisture. Corrosion does not occur in dry environments. However, some moisture is present as water vapor in most environments.

In pure oxygen, almost no iron corrosion occurs at relative humidities up to 99%. However, when contaminants such as sulfur dioxide or solid particles of charcoal are present, corrosion can proceed at relative humidities of 50% or more. The corrosion reaction proceeds on surfaces of exposed metals such as iron and unalloyed steel as long as the metal remains wet. Many alloys develop protective corrosion-product films or oxide coatings and are thus unaffected by moisture.

Oxygen. In electrolytes consisting of water solutions of salts or acids, the presence of dissolved oxygen accelerates the corrosion rate of ferrous metals by depolarizing the cathodic areas through reaction with hydrogen generated at the cathode. In many systems, such as boilers or water heaters, most of the dissolved oxygen and other dissolved gases are removed from the water by deaeration to reduce the potential for corrosion.

Solutes. In ferrous materials such as iron and steel, mineral acids accelerate the corrosion rate, whereas alkalis decrease it. The likelihood of cathodic polarization, which slows down corrosion, decreases as the concentration of hydrogen ions (i.e., the acidity of the environment) increases. Relative acidity or alkalinity of a solution is defined as pH; a neutral solution has a pH of 7. The corrosivity of most salt solutions depend on their pH. Because alkaline solutions are generally less corrosive to ferrous systems, it is practical in many closed water systems to minimize corrosion by adding alkali or alkaline salt to raise the pH to 9 or higher.

Differential Solute Concentration. For the corrosion reaction to proceed, a potential difference between anode and cathode areas is required. This potential difference can be established between different locations on a metal surface because of differences in solute concentration in the environment at these locations. Corrosion caused by such conditions is called **concentration cell corrosion**. These cells can be metal ions or oxygen concentration cells.

In the metal ion cell, the metal surface in contact with the higher concentration of dissolved metal ion becomes the cathodic area, and the surface in contact with the lower concentration becomes the anode. The metal ions involved may be a constituent of the environment or may come from the corroding surface itself. The concentration differences may be caused by the sweeping away of the dissolved metal ions at one location and not at another.

In an oxygen concentration cell, the surface area in contact with the surface environment of higher oxygen concentration becomes the cathodic area, and the surface in contact with the surface environment of lower oxygen concentration becomes the anode. Crevices or foreign deposits on the metal surface can create conditions that contribute to corrosion. The anodic area, where corrosion proceeds, is in the crevice or under the deposit. Although they are manifestations of concentration cell corrosion, **crevice corrosion** and **deposit attack** are sometimes referred to as separate forms of corrosion.

Galvanic or Dissimilar Metal Corrosion. Another factor that can accelerate the corrosion process is the difference in potential of dissimilar metals coupled together and immersed in an electrolyte. The following factors control the severity of corrosion resulting from such dissimilar metal coupling:

- Relative differences in position (potential) in the galvanic series, with reference to a standard electrode. The greater the difference, the greater the force of the reaction. The galvanic series for metals in flowing aerated seawater is shown in [Table 2](#).
- Relative area relationship between anode and cathode areas. Because the amount of current flow and, therefore, total metal loss is determined by the potential difference and resistance of the circuits, a small anodic area corrodes more rapidly; it is penetrated at a greater rate than a large anodic area.
- Polarization of either the cathodic or anodic area. Polarization can reduce the potential difference and thus reduce the rate of attack of the anode.

Table 2 Galvanic Series of Metals and Alloys in Flowing Aerated Seawater at 4 to 27°C

Corroded End (Anodic or Least Noble)
Magnesium alloys
Zinc
Beryllium
Aluminum alloys
Cadmium
Mild steel, wrought iron
Cast iron, flake or ductile
Low-alloy high-strength steel
Ni-Resist, Types 1 & 2
Naval Brass (CA464), yellow brass (CA268), Al brass (CA687), red brass (CA230), admiralty brass (CA443), Mn Bronze
Tin
Copper (CA102, 110), Si Bronze (CA655)
Lead-tin solder
Tin bronze (G & M)
Stainless steel, 12 to 14% Cr (AISI types 410,416)
Nickel silver (CA 732, 735, 745, 752, 764, 770, 794)
90/10 Copper-nickel (CA 706)
80/20 Copper-nickel (CA 710)
Stainless steel, 16 to 18% Cr (AISI Types 430)
Lead
70/30 Copper-nickel (CA 715)
Nickel-aluminum bronze
Silver braze alloys
Nickel 200
Silver
Stainless steel, 18% Cr, 8% Ni (AISI Types 302, 304, 321, 347)
Stainless steel, 18% Cr, 12% Ni-Mo (AISI Types 316, 317)
Titanium
Graphite, graphitized cast iron
Protected End (Cathodic or Most Noble)

- The mineral content of water. As mineral content increases, the resulting higher electrical conductivity increases the rate of galvanic corrosion.

Stress. Stresses in metallic structures rarely have significant effects on the uniform corrosion resistance of metals and alloys. Stresses in specific metals and alloys can cause corrosion cracking when the metals are exposed to specific corrosive environments. The cracking can have catastrophic effects on the usefulness of the metal.

Almost all metals and alloys exhibit susceptibility to stress corrosion cracking in at least one environment. Common examples are steels in hot caustic solutions, high zinc content brasses in ammonia, and stainless steels in hot chlorides. Metal manufacturers have technical details on specific materials and their resistance to stress corrosion.

Temperature. According to studies of chemical reaction rates, corrosion rates double for every 10 K rise in temperature. However, such a ratio is not necessarily valid for nonlaboratory corrosion reactions. The effect of temperature on a particular system is difficult to predict without specific knowledge of the characteristics of the metals involved and the environmental conditions.

An increase in temperature may increase the corrosion rate, but only to a point. Oxygen solubility decreases as temperature increases and, in an open system, may approach zero as water boils. Beyond a critical temperature level, the corrosion rate may decrease due to a decrease in oxygen solubility. However, in a closed system, where oxygen cannot escape, the corrosion rate may continue to increase with an increase in temperature.

For those alloys, such as stainless steel, that depend on oxygen in the environment for maintaining a protective oxide film, the reduction in oxygen content due to an increase in temperature can accelerate the corrosion rate by preventing oxide film formation.

Temperature can affect corrosion potential by causing a salt dissolved in the environment to precipitate on the metal surface as a

protective layer of scale. One example is calcium carbonate scale in hard waters. Temperature can also affect the nature of the corrosion product, which may be relatively stable and protective in certain temperature ranges and unstable and non protective in others. An example of this is zinc in distilled water; the corrosion product is non protective from 60 to 80°C but reasonably protective at other temperatures.

Pressure. Where dissolved gases such as oxygen and carbon dioxide affect the corrosion rate, pressure on the system may increase their solubility and thus increase corrosion. Similarly, a vacuum on the system reduces the solubility of the dissolved gas, thus reducing corrosion. In a heated system, pressure may rise with temperature. It is difficult and impractical to control system corrosion by pressure control alone.

Flow Velocity. The effect of flow velocity on the corrosion rate of systems depends on several factors, including

- Amount of oxygen in the water
- Type of metal (iron and steel are most susceptible)
- Flow rate

In metal systems where corrosion products retard corrosion by acting as a physical barrier, high flow velocities may cause the removal of those protective barriers and increase the potential for corrosion. A turbulent environment may cause uneven attack, from both erosion and corrosion. This corrosion is called **erosion corrosion**. It is commonly found in piping with sharp bends where the flow velocity is high. Copper and softer metals are more susceptible to this type of attack.

Preventive and Protective Measures

Materials Selection. Any piece of heating or air-conditioning equipment can be made of metals that are virtually corrosion-proof under normal and typical operating conditions. However, economics usually dictate material choices. When selecting construction materials the following factors should be considered:

- Corrosion resistance of the metal in the operating environment
- Corrosion products that may be formed and their effects on equipment operation
- Ease of construction using a particular material
- Design and fabrication limitations on corrosion potential
- Economics of construction, operation, and maintenance during the projected life of the equipment, (i.e., expenses may be minimized in the long run by paying more for a corrosion-resistant material and avoiding regular maintenance).
- Use of dissimilar metals should be avoided. Where dissimilar materials are used, insulating gaskets and/or organic coatings must be used to prevent galvanic corrosion.
- Compatibility of chemical additives with materials in the system

Protective Coatings. The operating environment has a significant role in the selection of protective coatings. Even with a coating suited for that environment, the protective material depends on the adhesion of the coating to the base material, which itself depends on the surface preparation and application technique.

Maintenance. Defects in a coating are difficult to prevent. These defects can be either flaws introduced into the coating during application or mechanical damage sustained after application. In order to maintain corrosion protection, defects must be repaired.

Cycles of Concentration. Some corrosion control may be achieved by optimizing the cycles of concentration (the degree to which soluble mineral solids in the makeup water have increased in the circulating water due to evaporation). Generally, adjustment of the blowdown rate and pH to produce a slightly scale-forming condition (see section on Scale Control) will result in an optimum condition between excess corrosion and excess scale.

Chemical Methods. Chemical protective film-forming chemical inhibitors reduce or stop corrosion by interfering with the

Table 3 Typical Corrosion Inhibitors

Anodic Corrosion Inhibitors	
Molybdate	
Nitrite	
Orthophosphate	
Silicate	
Mainly Cathodic Corrosion Inhibitors	
Bicarbonate	
Polyphosphate	
Phosphonate	
Zinc	
Polysilicate	
General	
Soluble oils	
Other organics, such as azole or carboxylate	

corrosion mechanism. Inhibitors usually affect either the anode or the cathode.

Anodic corrosion inhibitors establish a protective film on the anode. Though these inhibitors can be effective, they can be dangerous—if insufficient anodic inhibitor is present, the entire corrosion potential occurs at the unprotected anode sites. This causes severe localized (or pitting) attack.

Cathodic corrosion inhibitors form a protective film on the cathode. These inhibitors reduce the corrosion rate in direct proportion to the reduction of the cathodic area.

General corrosion inhibitors protect by forming a film on all metal surfaces whether anodic or cathodic.

Table 3 lists typical corrosion inhibitors. The most important factor in an effective corrosion inhibition program is the consistent control of both the corrosion inhibition chemicals and the key water characteristics. No program will work without controlling these factors.

Cathodic Protection. Sacrificial anodes reduce galvanic attack by providing a metal (usually zinc, but sometimes magnesium) that is higher on the galvanic series than either of the two metals that are coupled together. The sacrificial anode thereby becomes anodic to both metals and supplies electrons to these cathodic surfaces. Proper design and placement of these anodes are important. When properly used, they can reduce loss of steel from the tube sheet of exchangers using copper tubes. Sacrificial anodes have helped supplement chemical programs in many cooling water and process water systems.

Impressed-current protection is a similar corrosion control technique that reverses the corrosion cell's normal current flow by impressing a stronger current of opposite polarity. Direct current is applied to an anode—inert (platinum, graphite) or expendable (aluminum, cast iron)—reversing the galvanic flow and converting the steel from a corroding anode to a protective cathode. The method is very effective in protecting essential equipment such as elevated water storage tanks, steel tanks, or softeners.

White Rust on Galvanized Steel Cooling Towers

White rust is a zinc corrosion product that forms on galvanized surfaces. It appears as a white, waxy or fluffy deposit composed of loosely adhering zinc carbonate. The loose crystal structure allows continued access of the corrosive water to exposed zinc. Unusually rapid corrosion of galvanized steel, as evidenced by white rust, can affect galvanized steel cooling towers under certain conditions.

Before chromates in cooling tower water were banned, the common treatment system consisted of chromates for corrosion control and sulfuric acid for scale control. This control method generally has been replaced by alkaline treatment involving scale inhibitors at a higher pH. Alkaline water chemistry is naturally less corrosive to steel and copper, but create an environment where white rust on galvanized steel can occur. Also, some scale prevention programs soften the water to reduce hardness, rather

than use acid to reduce alkalinity. The resulting soft water is corrosive to galvanized steel.

Prevention. White rust can be prevented by promoting the formation of a nonporous surface layer of basic zinc carbonate. This barrier layer is formed during a process called **passivation** and normally protects the galvanized steel for many years. Passivation is best accomplished by controlling pH during initial operation of the cooling tower. Control of the cooling water pH in the range of 7 to 8 for 45 to 60 days usually allows passivation of galvanized surfaces to occur. In addition to pH control, operation with moderate hardness levels of 100 to 300 mg/kg as CaCO_3 and alkalinity levels of 100 to 300 mg/kg as CaCO_3 will promote passivation. Where pH control is not possible, certain phosphate-based inhibitors may help protect galvanized steel. A water treatment company should be consulted for specific formulations.

SCALE CONTROL

Scale is a dense coating of predominantly inorganic material formed from the precipitation of water-soluble constituents. Some common scales are

- Calcium carbonate
- Calcium phosphate
- Magnesium salts
- Silica

The following principal factors determine whether or not a water is scale forming:

- Temperature
- Alkalinity or acidity (pH)
- Amount of scale-forming material present
- Influence of other dissolved materials, which may or may not be scale-forming

As any of these factors changes, scaling tendencies also change. Most salts become more soluble as temperature increases. However, some salts, such as calcium carbonate, become less soluble as temperature increases. Therefore, they often cause deposits at higher temperatures.

A change in pH or alkalinity can greatly affect scale formation. For example, as pH or alkalinity increases, calcium carbonate—the most common scale constituent in cooling systems—decreases in solubility and deposits on surfaces. Some materials, such as silica (SiO_2), are less soluble at lower alkalinities. When the amount of scale-forming material dissolved in water exceeds its saturation point, scale may result. In addition, other dissolved solids may influence scale-forming tendencies. In general, a higher level of scale-forming dissolved solids results in a greater chance for scale formation. Indices such as the Langelier Saturation Index (Langelier 1936) and the Ryznar Stability Index (Ryznar 1944) can be useful tools to predict the calcium carbonate scaling tendency of water. These indices are calculated using the pH, alkalinity, calcium hardness, temperature, and total dissolved solids of the water, and indicate whether the water will favor precipitating or dissolving of calcium carbonate.

Methods used to control scale formation include

- Limit the concentration of scale-forming minerals by controlling cycles of concentration or by removing the minerals before they enter the system (see the section on External Treatments later in this section). **Cycles of concentration** is the ratio of makeup rate to the sum of blowdown and drift rates. The cycles of concentration can be monitored by calculating the ratio of chloride ion, which is highly soluble, in the system water to that in the makeup water.
- Make mechanical changes in the system to reduce the chances for scale formation. Increased water flow and exchangers with larger surface areas are examples.

- Feed acid to keep the common scale forming minerals (e.g., calcium carbonate) dissolved.
- Treat with chemicals designed to prevent scale. Chemical scale inhibitors work by the following mechanisms:
 1. **Threshold inhibition chemicals** prevent scale formation by keeping the scale forming minerals in solution and not allowing a deposit to form. Threshold inhibitors include organic phosphates, polyphosphates, and polymeric compounds.
 2. **Scale conditioners** modify the crystal structure of scale, creating a bulky, transportable sludge instead of a hard deposit. Scale conditioners include lignins, tannins, and polymeric compounds.

Nonchemical Methods

Equipment based on magnetic, electromagnetic, or electrostatic technology has been used for scale control in boiler water, cooling water, and other process applications.

Magnetic systems are designed to cause scale-forming minerals to precipitate in a low-temperature area away from heat exchanger surfaces, thus producing nonadherent particles (e.g., aragonite form of calcium carbonate versus the hard, adherent calcite form). The precipitated particles can then be removed by blowdown, mechanical means, or physical flushing. The effectiveness of a magnetic system can be diminished by a low ratio of dissolved calcium to silica, by the presence of excessive iron in the water, or if it is installed in close proximity to high-voltage power lines.

The objective of **electrostatics** is to prevent scale-forming reactions by imposing a surface charge on dissolved ions that causes them to repel.

Results of side-by-side comparative tests with conventional water treatment have been mixed. A Federal Technology Alert report regarding these technologies (DOE 1998) stresses that success of the application depends largely on the experience of the installer. The report includes a discussion of the potential benefits achieved and the necessary precautions to consider when applying these systems.

External Treatments

Minerals may also be removed by various external pretreatment methods such as reverse osmosis and ion exchange. Zeolite softening, demineralization, and dealkalization are examples of ion exchange processes.

BIOLOGICAL GROWTH CONTROL

Biological growth (algae, bacteria, and fungi) can interfere with a cooling operation due to fouling or corrosion, and may present a health hazard if present in aerosols produced by the equipment. Heating equipment operates above normal biological limits and therefore has fewer microbial problems. When considering biological growth in a cooling system, it is important to distinguish between free-living planktonic organisms and sessile (attached) organisms. Sessile organisms cause the majority of the problems, though they may have entered and multiplied as planktonic organisms.

Biological fouling can be caused by a wide variety of organisms that produce biofilm and slime masses. Slimes can be formed by bacteria, algae, yeasts, or molds and frequently consist of a mixture of these organisms combined with organic and inorganic debris. Organisms such as barnacles and mussels may cause fouling when river, estuarine, or sea water is used. Biological fouling can significantly reduce the efficiency of cooling by reducing heat transfer, increasing back pressure on recirculation pumps, disrupting flow patterns over cooling media, plugging heat exchangers, and blocking distribution systems. In extreme cases the additional mass of slime has caused the cooling media to collapse.

Microorganisms can dramatically enhance, accelerate or, in some cases, initiate localized corrosion (pitting). Microorganisms

can influence localized corrosion directly by their metabolism or indirectly by the deposits they form. Indirect influence may not be mediated by simply killing the microorganisms; deposit removal is usually necessary, while direct influence can be substantially mediated by inhibiting microorganism metabolism.

Algae use energy from the sun to convert bicarbonate or carbon dioxide into biomass. Masses of algae can block piping, distribution holes, and nozzles. A distribution deck cover, which drastically reduces the sunlight reaching the algae, is one of the most cost-effective control devices for a cooling tower. Biocides are also used to assist in the control of algae.

Algae can also provide nutrients for other microorganisms in the cooling system, increasing the biomass in the water. Bacteria can grow in systems even when nutrient levels are relatively low. Yeasts and fungi are much slower growing than bacteria and find it difficult to compete in bulk waters for the available food. Fungi do thrive in partially wetted and high humidity areas such as the cooling media. Wood-destroying species of fungi can be a major concern for wooden cooling towers as the fungi consume the cellulose and/or lignin in the wood, reducing its structural integrity.

Most waters contain organisms capable of producing biological slime, but optimal conditions for growth are poorly understood. Equipment near nutrient sources or that has process leaks acting as a food source is particularly susceptible to slime formation. Even a thin layer of biofilm significantly reduces heat transfer rates in exchangers.

Control Measures

Eliminating sunlight from wetted surfaces such as distribution troughs, cooling media, and sumps significantly reduces algae growth. Eliminating deadlegs and low flow areas in the piping and the cooling loop reduces biological growth in those areas. Careful selection of materials of construction can remove nutrient sources and environmental niches for growth. Maintaining a high quality makeup water supply with low bacteria counts also helps minimize biological growth. Equipment should also be designed with adequate access for inspection, sampling, and manual cleaning.

Sometimes the effective control of slime and algae requires a combination of mechanical and chemical treatments. For example, when a system already contains a considerable accumulation of slime, a preliminary mechanical cleaning makes the subsequent application of a biocidal chemical more effective in killing the growth and more effective in preventing further growth. A build-up of scale deposits, corrosion product, and sediment in a cooling system also reduces the effectiveness of chemical biocides. Routine manual cleaning of cooling towers, including the use of high level chlorination and a biodispersant (surfactant), helps control *Legionella* bacteria as well as other microorganisms.

Microbiocides. Chemical biocides used to control biological growth in cooling systems fall into two broad categories: oxidizing and nonoxidizing biocides.

Oxidizing biocides (chlorine, chlorine-yielding compounds, bromine, bromochlorodimethylhydantoin (BCDMH, or BCD), ozone, iodine, and chlorine dioxide) are among the most effective microbiocidal chemicals. However, they are not always appropriate for control in cooling systems with a high organic loading. In air washers, the odor may become offensive; in wooden cooling towers, excessive concentrations of oxidizing biocides can cause delignification; and overdosing of oxidizing biocides may cause corrosion of metallic components. In systems large enough to justify the cost of equipment to control feeding of oxidizing biocides accurately, the application may be safe and economical. The most effective use of oxidizing biocides is to maintain a constant low level residual in the system. However, if halogen-based oxidizing biocides are fed intermittently (slug dosed), a pH near 7 is advantageous because, at this neutral pH, halogens are present as the hypohalous acid (HOR, where R represents the halogen) form over the hypohalous ion

(OR⁻) form. The effectiveness of this shock feeding is enhanced due to the faster killing action of hypohalous acid over that of hypohalous ion. The residual biocide concentration should be tested, using a field test kit, on a routine basis. Most halogenation programs can benefit from the use of dispersants or surfactants (chlorine helpers) to break up microbiological masses.

Chlorine has been the oxidizing biocide of choice for many years, either as chlorine gas or in the liquid form as sodium hypochlorite. Other forms of chlorine, such as powders or pellets, are also available. Use of chlorine gas is declining due to the health and safety concerns involved in handling this material and in part due to environmental pressures concerning the formation of chloramines and trihalomethane.

Bromine is produced either by the reaction of sodium hypochlorite with sodium bromide on site, or by release from pellets. Bromine has certain advantages over chlorine: it is less volatile, and bromamines break down more rapidly than chloramines in the environment. Also, when slug feeding biocide in high pH systems, hypobromous acid may have an advantage because its dissociation constant is lower than that of chlorine. This effect is less important when biocides are fed continuously.

Ozone has several advantages compared to chlorine: it does not produce chloramines or trihalomethane, it breaks down to nontoxic compounds rapidly in the environment, it controls biofilm better, and it requires significantly less chemical handling. The use of ozone-generating equipment in an enclosed space however, requires care be taken to protect operators from the toxic gas. Also, research by ASHRAE has shown that ozone is only marginally effective as a scale and corrosion inhibitor (Gan et al. 1996, Nasrazadani and Chao 1996).

Water conditions should be reviewed to determine the need for scale and corrosion inhibitors and then, as with all oxidizing biocides, inhibitor chemicals should be carefully selected to ensure compatibility. To maximize the biocidal performance of the ozone, the injection equipment should be designed to provide adequate contact of the ozone with the circulating water. In larger systems, care should be taken to ensure that the ozone is not depleted before the water has circulated through the entire system.

Iodine is provided in pelletized form, often from a rechargeable cartridge. Iodine is a relatively expensive chemical for use on cooling towers and is probably only suitable for use on smaller systems.

Nonoxidizing Biocides. When selecting a nonoxidizing microbicide, the pH of the circulating water and the chemical compatibility with the corrosion and/or scale inhibitor product must be considered. The following list, while not exhaustive, identifies some of these products:

- Quaternary ammonium compounds
- Methylene bis(thiocyanate) (MBT)
- Isothiazolones
- Thiadiazine thione
- Dithiocarbamates
- Decyl thioethanamine (DTEA)
- Glutaraldehyde
- Dodecylguanidine
- Benzotriazole
- Tetrakis(hydroxymethyl)phosphonium sulfate (THPS)
- Dibromo-nitrilopropionamide (DBNPA)
- Bromo-nitropropane-diol
- Bromo-nitrostyrene (BNS)
- Proprietary blends

The manner in which nonoxidizing biocides are fed is important. Sometimes the continuous feeding of low dosages is neither effective nor economical. Slug feeding large concentrations to achieve a toxic level of the chemical in the water for a sufficient time to kill the organisms present can show better results. Water blowdown rate and biocide hydrolysis (chemical degradation) rate affect the required

dosage. The hydrolysis rate of the biocide is affected by the type of biocide, along with the temperature and pH of the system water. Dosage rates are proportional to system volume; dosage concentrations should be sufficient to ensure that the contact time of the biocide is long enough to obtain a high kill rate of microorganisms before the minimum inhibitory concentration of the biocide is reached. The period between nonoxidizing biocide additions should be based on the system half life, with sequential additions timed to prevent regrowth of bacteria in the water.

Handling Microbiocides. All microbiocides must be handled with care to ensure personal safety. In the United States, cooling water microbiocides are approved and regulated through the EPA and, by law, must be handled in accordance with labeled instructions. Maintenance staff handling the biocides should read the material safety data sheets and be provided with all the appropriate safety equipment to handle the substance. Automatic feed systems should be used that minimize and eliminate the handling of biocides by maintenance personnel.

Other Biocides. **Ultraviolet irradiation** deactivates the microorganisms as the water passes through a quartz tube. The intensity of the light and thorough contact with the water are critical in obtaining a satisfactory kill of microorganisms. Suspended solids in the water or deposits on the quartz tube significantly reduce the effectiveness of this treatment method. Therefore, a filter is often installed upstream of the lamp to minimize these problems. Because the ultraviolet light leaves no residual material in the water, sessile organisms and organisms that do not pass the light source are not affected by the ultraviolet treatment. Ultraviolet irradiation may be effective on humidifiers and air washers where the application of biocidal chemicals is unacceptable and where 100% of the recirculating water passes the lamp. Ultraviolet irradiation is less effective where all the microorganisms cannot be exposed to the treatment, such as in cooling towers. Ultraviolet lamps require replacement after approximately every 8000 h of operation.

Metallic ions, namely copper and silver, effectively control microbial populations under very specific circumstances. Either singularly or in combination, copper and silver ions are released into the water via electrochemical means to generate 1 to 2 mg/kg of copper and/or 0.5 to 1.0 mg/kg of silver. The ions assist in the control of bacterial populations in the presence of a free chlorine residual of at least 0.2 mg/kg. Copper, in particular, effectively controls algae.

Liu et al. (1994) reported control of *Legionella pneumophila* bacteria in a hospital hot water supply using copper-silver ionization. In this case, *Legionella* colonization decreased significantly when copper and silver concentrations exceeded 0.4 and 0.04 mg/kg, respectively. Also, residual disinfection prevented *Legionella* colonization for two months after the copper-silver unit was inactivated.

Significant limitations exist in the use of copper and silver ion for cooling systems. Many states are restricting the discharge of these ions to surface waters, and if the pH of the system water rises above 7.8, the efficacy of the treatment is significantly reduced. Systems that have steel or aluminum heat exchangers should not be treated by this method, as the potential for the deposition of the copper ion and subsequent galvanic corrosion is significant.

Legionnaires' Disease

Like other living things, *Legionella pneumophila*, the bacterium that causes Legionnaires' disease (legionellosis), requires moisture for survival. *Legionella* bacteria are widely distributed in natural water systems and are present in many drinking water supplies. Potable hot water systems between 27 and 50°C, cooling towers, certain types of humidifiers, evaporative condensers, whirlpools and spas, and the various components of air conditioners are considered to be amplifiers. These bacteria are killed in a matter of minutes when exposed to temperatures above 60°C.

Legionellosis can be acquired by inhalation of *Legionella* organisms in aerosols. Aerosols can be produced by cooling towers,

evaporative condensers, decorative fountains, showers, and misters. It has been reported that the aerosol from cooling towers can be transmitted over a distance of up to 3 km. If air inlet ducts of nearby air conditioners draw the aerosol from contaminated cooling towers into the building, the air distribution system itself can transmit the disease. When an outbreak of Legionnaires' disease occurs, cooling towers are often the suspected source. However, other water systems may produce an aerosol and should not be neglected. Amplification of *Legionella* within protozoans has been demonstrated, and *Legionella* bacteria are thought to be protected from biocides while growing intracellularly. Amplification of *Legionella* bacteria in biofilm and slime masses has been shown by a number of researchers. Microbial control programs should consider the effectiveness of the products against slimes as part of the *Legionella* control program.

Humidifiers. Units that generate a water aerosol for humidity control can become amplifiers of bacteria if their reservoirs are poorly maintained. Manufacturers' recommendations on cleaning and maintenance should be followed closely. Steam humidifiers should not pose a bacterial problem because the steam does not contain bacteria.

Whirlpools and Spas. These units pose a potential hazard to users if not properly maintained. The complexity of some units makes cleaning difficult, so a firm that specializes in cleaning these devices may need to be hired. Manufacturers' instructions should be followed carefully.

Decorative Fountains. If these systems become contaminated, *Legionella* may multiply and pose a hazard to those nearby. The recirculating water should be kept clean and clear with proper filtration. Continuous chlorination or use of another biocide with EPA approval for decorative fountains is recommended. Indoor decorative fountains with ponds containing fish and other aquatic life cannot be chlorinated or treated; steps should be taken to ensure that water does not become airborne via sprays or cascading waterfalls.

Roof Ponds. These are used to lower the roof temperature and thus the demand on the air conditioning. If contaminated, such ponds can pose a risk to the staff and general public. Roof ponds should be monitored and treated in the same manner as recirculating cooling water systems (see the section on Selection of Water Treatment).

Safety Showers. Safety showers are mandated for safety, but they are used infrequently. Standing reservoirs of nonsterile water at room temperature should be avoided. A preventative maintenance program that includes flushing is suggested.

Vegetable Mistors or Sprays. Although an older-style ultrasonic mist machine has been implicated in at least one case of this disease, once-through cool-water sprayers, (directly connected to a cold, potable water line with no reservoir) do not appear to be a problem.

Machine Shop Cooling. Water used in machining operations may be mixed with oil or other ingredients to improve cooling and cutting efficiency. It is typically stored in holding tanks that are subject to bacterial contamination, including by *Legionella*. Bacterial activity should be monitored and controlled.

Ice-Making Machines. While *Legionella* bacteria are not likely to amplify in this cold environment, bacterial amplification can occur prior to freezing the water. Graman et al. (1997) described a case in which *Legionella* were presumed to have been transmitted by aspiration of ice or ice water from an ice machine.

Prevention and Control. The *Legionella* count required to cause illness has not been firmly established because many factors are involved, including (1) virulence and number of *Legionella* in the air, (2) rate at which the aerosol dries, (3) wind direction, and (4) susceptibility to the disease of the person breathing the air. The organism is often found in sites not associated with an outbreak of the disease. It has been shown that it is feasible to operate cooling systems with *Legionella* bacteria below the limit of detection and that the only method to prove that a system is operating at these

levels is to specifically test for *Legionella* bacteria, rather than to infer from total bacteria count measurements.

Periodic monitoring of circulating water for total bacteria count and *Legionella* count can be accomplished using culture methods. However, routine culturing of samples from building water systems may not yield an accurate prediction of the risk of *Legionella* transmission. Monitoring system cleanliness and using a microbial control agent that has proven efficacy or is generally regarded as effective in controlling *Legionella* populations are also important. Other measures to decrease risk include optimizing cooling tower design to minimize drift, eliminating deadlegs or low flow areas, selecting materials that do not promote the growth of *Legionella*, and locating the tower so that drift is not injected into the air handlers. The *Legionellosis Position Statement*, an ASHRAE Position Paper (1998) has further information on this topic.

SUSPENDED SOLIDS AND DEPOSITION CONTROL

Mechanical Filtration

Strainers, filters, and separators may be used to reduce suspended solids to an acceptable low level. Generally, if the screen is 200 mesh, with an aperture of 74 μm , it is called a strainer; if it is finer than 200 mesh, it is called a filter.

Strainers. A strainer is a closed vessel with a cleanable screen designed to remove and retain foreign particles down to 25 μm diameter from various flowing fluids. Strainers extract material that is not wanted in the fluid, and allow saving the extracted product if it is valuable. Strainers are available as single-basket or duplex units, manual or automatic cleaning units, and may be made of cast iron, bronze, stainless steel, copper-nickel alloys, or plastic. Magnetic inserts are available where microscopic iron or steel particles are present in the fluid.

Cartridge Filters. These are typically used as final filters to remove nearly all suspended particles from about 100 μm down to 1 μm or less. Cartridge filters are typically disposable (i.e., once plugged, they must be replaced). The frequency of replacement, and thus the economical feasibility of their use, depends on the concentration of suspended solids in the fluid, the size of the smallest particles to be removed, and the removal efficiency of the cartridge filter selected.

In general, cartridge filters are favored in systems where contamination levels are less than 0.01% by mass ($< 100 \text{ mg/kg}$). They are available in many different materials of construction and configurations. Filter media materials include yarns, felts, papers, nonwoven materials, resin-bonded fabric, woven wire cloths, sintered metal, and ceramic structures. The standard configuration is a cylinder with an overall length of approximately 250 mm, an outside diameter of approximately 65 to 70 mm, and an inside diameter of about 25 to 40 mm, where the filtered fluid collects in the perforated internal core. Overall lengths from 0.1 to 1 m are readily available.

Cartridges made of yarns, resin-bonded, or melt-blown fibers normally have a structure that increases in density towards the center. These depth-type filters capture particles throughout the total media thickness. Thin media, such as pleated paper (membrane types), have a narrow pore size distribution design to capture particles at or near the surface of the filter. Surface-type filters can normally handle higher flow rates and provide higher removal efficiency than equivalent depth filters. Cartridge filters are rated according to manufacturers' guidelines. Surface-type filters have an absolute rating, while depth-type filters have a nominal rating that reflects their general classification function. Higher efficiency melt-blown depth filters are available with absolute ratings as needed.

Sand Filters. A downflow filter is used to remove suspended solids from a water stream. The degree of suspended solids removal depends on the combinations and grades of the medium being used in the vessel. During the filtration mode, water enters the top of the

filter vessel. After passing through a flow impingement plate, it enters the quiescent (calm) freeboard area above the medium.

In multimedia downflow vessels, various grain sizes and types of media are used to filter the water. This design increases the suspended solids holding capacity of the system, which in turn increases the backwashing interval. Multimedia vessels might also be used for low suspended solids applications, where chemical additives are required. In the multimedia vessel, the fluid enters the top layer of anthracite media, which has an effective size of 1 mm. This relatively coarse layer removes the larger suspended particles, a substantial portion of the smaller particles, and small quantities of free oil. Flow continues down through the next layer of fine garnet material, which has an effective size of 0.3 mm. A more finely divided range of suspended solids is removed in this polishing layer. The fluid continues into the final layer, a coarse garnet material that has an effective size of 2 mm. Contained in this layer is the header/lateral assembly that collects the filtered water.

When the vessel has retained enough suspended solids to develop a substantial pressure drop, the unit must be backwashed either manually or automatically by reversing the direction of flow. This operation removes the accumulated solids out through the top of the vessel.

Centrifugal-Gravity Separators. In this type of separator, liquids/solids enter the unit tangentially, which sets up a circular flow. Liquids/solids are drawn through tangential slots and accelerated into the separation chamber. Centrifugal action tosses the particles heavier than the liquid to the perimeter of the separation chamber. Solids gently drop along the perimeter and into the separator's quiescent collection chamber. Solids-free liquid is drawn into the separator's vortex (low-pressure area) and up through the separator's outlet. Solids are either purged periodically or continuously bled from the separator by either a manual or automatic valve system.

Bag Type Filters. These filters are composed of a bag of mesh or felt supported by a removable perforated metal basket, placed in a closed housing with an inlet and outlet. The housing is a welded, tubular pressure vessel with a hinged cover on top for access to the bag and basket. Housings are made of carbon or stainless steel. The inlet can be in the cover, in the side (above the bag), or in the bottom (and internally piped to the bag). The side inlet is the simplest type. In any case, the liquid enters the top of the bag. The outlet is located at the bottom of the side (below the bag). Pipe connections can be threaded or flanged. Single-basket housings can handle up to 14 L/s, multibaskets up to 220 L/s.

The support basket is usually of 304 stainless steel perforated with 3 mm holes. (Heavy wire mesh baskets also exist.) The baskets can be lined with fine wire mesh and used by themselves as strainers, without adding a filter bag. Some manufacturers offer a second, inner basket (and bag) that fits inside the primary basket. This provides for two-stage filtering: first a coarse filtering stage, then a finer one. The benefits are longer service time and possible elimination of a second housing to accomplish the same function.

The filter bags are made of many materials (cotton, nylon, polypropylene, and polyester) with a range of ratings from 0.01 mm to 0.85 mm. Most common are felted materials because of their depth-filtering quality, which provides high dirt-loading capability, and their fine pores. Mesh bags are generally coarser, but are reusable and, therefore, less costly. The bags have a metal ring sewn into their opening; this holds the bag open and seats it on top of the basket rim.

In operation, the liquid enters the bag from above, flows out through the basket, and exits the housing cleaned of particulate down to the desired size. The contaminant is trapped inside the bag, making it easy to remove without spilling any downstream.

Special Methods. Localized areas frequently can be protected by special methods. Thus, pump-packing glands or mechanical shaft seals can be protected by fresh water makeup or by circulating

water from the pump casing through a cyclone separator or filter, then into the lubricating chamber.

In smaller equipment, a good dirt-control measure is to install backflush connections and shutoff valves on all condensers and heat exchangers so that accumulated settled dirt can be removed by backflushing with makeup water or detergent solutions. These connections can also be used for acid cleaning to remove calcium carbonate scale.

In specifying filtration systems, third-party testing by a qualified university or private test agency should be requested. The test report documentation should include a description of methods, piping diagrams, performance data, and certification.

Filters described in this section may also be used where industrial process cooling water is involved. For this type of service, consultation with the filtration equipment manufacturer is essential to ensure proper application.

START-UP AND SHUTDOWN OF COOLING TOWER SYSTEMS

The following guidelines are for start-up (or recommissioning) and shutdown of cooling tower systems:

Start-Up and Recommissioning for Drained Systems

- Clean all debris, such as leaves and dirt from the cooling tower.
- Close building air intakes in the area of the cooling tower to prevent entrainment of biocide and biological aerosols in the building air handling systems.
- Fill the system with water. While operating the condensing water pump(s) and *prior to operating the cooling tower fans*, execute one of the following two biocidal treatment programs:
 1. Resume treatment with the biocide that had been used prior to shutdown. Use the services of the water treatment supplier. Maintain the maximum recommended biocide residual (for the specific biocide) for a period sufficient to bring the system under good biological control (residual and time varies with the biocide).
 2. Treat the system with sodium hypochlorite at a level of 4 to 5 mg/kg free chlorine residual at a pH of 7.0 to 7.6. The residual level of free chlorine must be held at 4 to 5 mg/kg for 6 h. Commercially available test kits can be used to measure the residual of free chlorine.
- Once one of the two biocidal treatment programs has been successfully completed, turn on the fan and the put the system in service. The standard water treatment program (including biocidal treatment) should be resumed at this time.

Start-Up and Recommissioning for Undrained (Stagnant) Systems

- Remove accessible solid debris from bulk water storage vessel.
- Close building air intakes in the area of the cooling tower to prevent entrainment of biocide and biological aerosols in the building air handlers.
- Perform one of the two biocide pretreatment procedures (described in the section on Start-Up for Drained Systems) directly to the bulk water storage vessel (cooling tower sump, draindown tank, etc.). *Do not circulate stagnant bulk cooling water over cooling tower fill or operate cooling tower fans during pretreatment.*
- Stagnant cooling water may be circulated with condenser water pumps if tower fill is bypassed. Otherwise, add approved biocide directly to the bulk water source and mix with manual or side-stream flow methods. Take care to prevent the creation of aerosol spray from the stagnant cooling water from any point in the cooling water system.
- When one of the two biocidal pretreatments has been successfully completed, the cooling water should be circulated over the tower

fill. If biocide residual is maintained at a satisfactory level for at least 6 h, the cooling tower fans may then be operated safely.

Shutdown

When the system is to be shut down for an extended period, the entire system (cooling tower, system piping, heat exchangers, etc.) should be flushed and drained using the following procedure:

- Add a dispersant and biocide to the system and recirculate for 12 to 24 h. Confer with a water treatment consultant for suitable chemicals and dosage levels.
- Shut down pumps and completely drain all water distribution piping and headers, as well as the cooling loop. Remove water and debris from dead heads and low areas in the piping, which may not have completely drained.
- Rinse silt and debris from the sump. Pay special attention to corners and crevices. Add a mild solution of detergent and disinfectant to the sump and rinse. If the sump does not completely drain, pump out the remaining water and residue.
- If the equipment cannot be completely drained and is exposed to cold temperatures, freeze protection may be required.

SELECTION OF WATER TREATMENT

As discussed in the previous sections, many methods are available to prevent or correct water-caused problems. The selection of the proper water treatment method, and the chemicals and equipment necessary to apply that method, depends on many factors. The chemical characteristics of the water, which change with the operation of the equipment, are important. Other factors contributing to the selection of proper water treatment are

- Economics
- Chemistry control mechanisms
- Dynamics of the operating system
- Design of major components (e.g., the cooling tower or boiler)
- Number of operators available
- Training and qualifications of personnel
- Preventive maintenance program

Once-Through Systems

Economics is an overriding concern in treating water for once-through systems (in which a very large volume of water passes through the system only once). Protection can be obtained with relatively little treatment per unit mass of water because the water does not change significantly in composition while passing through equipment. However, the quantity of water to be treated is usually so large that any treatment other than simple filtration or the addition of a few parts per million of a polyphosphate, silicate, or other inexpensive chemical may not be practical or affordable. Intermittent treatment with polyelectrolytes can help maintain clean conditions when the cooling water is sediment-laden. In such systems, it is generally less expensive to invest more in corrosion-resistant construction materials than to attempt to treat the water.

Open Recirculating Systems

In an open recirculating system with chemical treatment, more chemical must be present because the water composition changes significantly by evaporation. Corrosive and scaling constituents are concentrated. However, treatment chemicals also concentrate by evaporation; therefore, after the initial dosage, only moderate dosages maintain the higher level of treatment needed. The selection of a water treatment program for an open recirculating system depends on the following major factors:

- Economics
- Water quality
- Performance criteria (e.g., corrosion rate, bacteria count, etc.)
- System metallurgy

- Available staffing
- Automation capabilities
- Environmental requirements
- Water treatment supplier (some technologies are superior to others in terms of economics, ease of use, safety, and impact on the environment)

An open recirculating system is typically treated with a scale inhibitor, corrosion inhibitor, oxidizing biocide, nonoxidizing biocide, and possibly a dispersant. The exact treatment program depends on the previously mentioned conditions.

A water treatment control scheme for a cooling tower might include

- Chemistry and cycles of concentration control using a conductivity controller
- Alkalinity control using automatic injection of sulfuric acid based on pH
- Scale control using contacting water meters, proportional feed, or traced control technology
- Oxidizing biocide control using an ORP (oxidation-reduction potential) controller
- Nonoxidizing biocide control using timers and pump systems

Air Washers and Sprayed Coil Units

A water treatment program for an air washer or a sprayed coil unit is usually complex and depends on the purpose and function of the system. Some systems, such as sprayed coils in office buildings, are used primarily to control the temperature and humidity. Other systems are intended to remove dust, oil vapor, and other airborne contaminants from an airstream. Unless the water is properly treated, the fouling characteristics of the contaminants removed from the air can cause operating problems.

Scale control is important in air washers or sprayed coils providing humidification. The minerals in the water may become concentrated (by evaporation) enough to cause problems. Inhibitor/dispersant treatment commonly used in cooling towers are often used in air washers to control scale formation and corrosion.

Suitable dispersants and surfactants are often needed to control oil and dust removed from the airstream. The type of dispersant depends on the nature of the contaminant and the degree of contamination. For maximum operating efficiency, dispersants should produce minimal amounts of foam.

Control of slime and bacterial growth is also necessary in the treatment of air washers and sprayed coils. The potential for biological growth is enhanced, especially if the water contains contaminants that are nutrients for the microorganisms. Due to variations in conditions and applications of air-washing installations and the possibility of toxicity problems, individual treatment options should be discussed with water treatment experts before a program is chosen. All microbiocides applied in air washers must have specific regulatory approval.

Ice Machines

Lime scale formation, cloudy or “milky” ice, objectionable taste and odor, and sediment are the most frequently encountered water problems in ice machines. Lime scale formation is probably the most serious problem because it interferes with the harvest cycle by forming on the freezing surfaces, preventing the smooth release of ice from the surface to the harvest bin.

Scale is caused by dissolved minerals in the water. Water freezes in a pure state and dissolved minerals concentrate in the unfrozen water; some eventually deposit on the machine’s freezing surfaces as scale. As shown in [Table 4](#), the probability of scale formation in an ice machine varies directly with the concentrations of carbonate and bicarbonate in the water circulating in the machine.

Table 4 Amount of Scale in an Ice Machine

Total Alkalinity as Bicarbonate, mg/kg	Hardness as Calcium Carbonate, mg/kg			
	0 to 49	50 to 99	100 to 199	200 and up
0 to 49	None	Very light	Very light	Very light
50 to 99	Very light	Moderate	Moderate	Moderate
100 to 199	Very light	Troublesome	Troublesome	Heavy
200 and up	Very light	Troublesome	Heavy	Very heavy

Dirty or scaled-up ice makers should be thoroughly cleaned before the water treatment program is started. Water distributor holes should be cleared, and all loose sediment and other material should be flushed from the system. Existing scale can be removed by circulating an acid solution through the system.

Slowly soluble food-grade polyphosphates inhibit scale formation on freezing surfaces during normal operation by keeping hardness in solution. Although polyphosphates can inhibit lime scale in the ice-making section and help prevent sludge deposits of loose particles of lime scale in the sump, they do not eliminate the soft, milky, or white ice caused by a high concentration of dissolved minerals in the water.

Even with proper chemical treatment, recirculating water having a mineral content above 500 to 1000 mg/kg cannot produce clear ice. Increasing bleed off or reducing the thickness of the ice slab or the size of the cubes may mitigate the problem. However, demineralizing or distillation equipment is usually needed to prevent white ice production.

Another problem frequently encountered with ice machines is objectionable taste or odor. When water containing a material having an offensive taste or odor is used in an ice machine, the taste or odor is trapped in the ice. An activated carbon filter on the makeup water line can remove the objectionable material from the water. Carbon filters must be serviced or replaced regularly to avoid organic buildup in the carbon bed.

Occasionally, slime growth causes an odor problem in an ice machine. This problem can be controlled by regularly cleaning the machine with a food-grade acid. If slime deposits persist, sterilization of the ice machine may be helpful.

Feedwater often contains suspended solids such as mud, rust, silt, and dirt. To remove these contaminants, a sediment filter of appropriate size can be installed in the feed lines.

Closed Recirculating Systems

In a closed recirculating system, water composition remains fairly constant with very little loss of either water or treatment chemical. Closed systems are often defined as those requiring less than 5% makeup per year. The need for water treatment in such systems (i.e., water heating, chilled water, combined cooling and heating, and closed loop condenser water systems) is often ignored based on the rationalization that the total amount of scale from the water initially filling the system would be insufficient to interfere significantly with heat transfer, and that corrosion would not be serious. However, leakage losses are common, and corrosion products can accumulate sufficiently to foul heat transfer surfaces. Therefore, all systems should be adequately treated to control corrosion. Systems with high makeup rates should be treated to control scale as well.

The selection of a treatment program for closed systems should consider the following factors:

- Economics
- System metallurgy
- Operating conditions
- Makeup rate
- System size

Possible treatment technologies include

- Buffered nitrite
- Molybdate
- Silicates
- Polyphosphates
- Oxygen scavengers
- Organic blends

Before new systems are treated, they must be cleaned and flushed. Grease, oil, construction dust, dirt, and mill scale are always present in varying degrees and must be removed from the metallic surfaces to ensure adequate heat transfer and to reduce the opportunity for localized corrosion. Detergent cleaners with organic dispersants are available for proper cleaning and preparation of new closed systems.

Water Heating Systems

Secondary and Low-Temperature. Closed, chilled-water systems that are converted to secondary water heating during winter and primary low-temperature water heating, both of which usually operate in the range of 60 to 120°C, require sufficient inhibitors to control corrosion to less than 125 µm per year. Ethylene glycol or propylene glycol may be used as antifreeze in secondary hot water systems. Such glycols are available commercially, with inhibitors such as sodium nitrite, potassium phosphate, and organic inhibitors for nonferrous metals added by the manufacturer. These require no further treatment, but softened water should be used for all filling and makeup requirements. Samples should be checked periodically to ensure that the inhibitor has not been depleted. Analytical services are available from the glycol manufacturers and others for this purpose.

Environment- and High-Temperature. Environment-temperature water heating systems (120 to 175°C) and high-temperature, high-pressure hot water systems (above 175°C) require careful consideration of treatment for corrosion and deposit control. Makeup water for such systems should be demineralized or softened to prevent scale deposits. For corrosion control, oxygen scavengers such as sodium sulfite can be added to remove dissolved oxygen.

Electrode boilers are sometimes used to supply low- or high-temperature hot water. Such systems use heat generated due to the electrical resistance of the water between electrodes. The conductivity of the recirculating water must be in a specific range depending on the voltage used. Treatment of this type of system for corrosion and deposit control varies. In some cases oil-based corrosion inhibitors that do not contribute to the conductivity of the recirculating water are used.

Brine Systems

Systems containing brine, a strong solution of sodium chloride or calcium chloride, must be treated to control corrosion and deposits. Sodium nitrite at a minimum 3000 mg/kg in calcium brines or 4000 mg/kg in sodium brines, and a pH between 7.0 and 8.5 should provide adequate protection. Organic inhibitors are available that may provide adequate protection where nitrites cannot be used. Molybdates should not be used with calcium brines because insoluble calcium molybdate will precipitate.

Boiler Systems

Many treatment methods are available for steam-producing boilers; the method selected depends on

- Makeup water quality
- Makeup water quantity (or percentage condensate return)
- Pretreatment equipment
- Boiler operating conditions
- Steam purity requirements
- Economics

Pretreatment for makeup water could consist of

- Water softeners (for removal of calcium and magnesium hardness)
- Deaerators (for removal of dissolved gases; especially oxygen and carbon dioxide)
- Dealkalizers (to remove alkalinity in systems with high makeup rates and high alkalinity makeup water)
- Demineralizers (to remove almost all the hardness, alkalinity, and solids, depending on the application)
- Reverse osmosis (can remove up to 99% of minerals and dissolved solids from the water leaving almost pure H₂O)

Contaminants that are not removed mechanically by pretreatment equipment must be treated chemically. Once in the feedwater, dissolved gases, hardness, and dissolved minerals must be treated to prevent deposition and corrosion. ASME (1994) and ABMA (1995) have published recommended water chemistry limits for boiler water.

Treatment of the boiler water is often determined by the end use of the steam. Treatment regimens may include reduction of alkalinity; hardness removal; silica removal; oxygen reduction; and the feed of scale and corrosion inhibitors, oxygen scavengers, condensate treatment chemicals, and antifoams. These regimens are described in the following paragraphs.

Prevention of Scale. After the feedwater is pretreated, scale is controlled with phosphates, acrylates, polymers, chelates, and coagulation programs. Chelates, polymers, and acrylates work by binding the hardness, thereby preventing precipitation and scale formation. Phosphates and coagulation programs work in combination with sludge conditioners (tannins, lignins, starches, and synthetic polymers) to produce a softened precipitate that is removed by blowdown of the boiler.

Prevention of Corrosion and Oxygen Pitting. While boilers can corrode as the result of low boiler water pH or misuse of certain chemicals, corrosion is primarily caused by oxygen. After mechanical deaeration, boiler feedwater must be treated chemically. Effective deaeration removes most of the dissolved oxygen. (Most properly operating deaerators can remove oxygen down to 0.007 mg/kg and deaerating heaters can remove oxygen down to 0.04 mg/kg.) Oxygen scavengers such as catalyzed sodium sulfite and proprietary organic oxygen scavengers should then be fed to react with the residual oxygen in feedwater after deaeration. Oxygen scavengers will not only provide added protection to the boiler but to the steam and condensate system as well. Oxygen at levels as low as 0.005 mg/kg can cause oxygen pitting in the steam and condensate system if not chemically reduced by oxygen scavengers.

Most of the corrosion damage to boilers and associated equipment occurs during idle periods. The corrosion is caused by the exposure of wet metal to oxygen in the air or water. For this reason, special precautions must be taken to prevent corrosion while boilers are out of service.

Wet Boiler Lay-Up. This is a method of storing boilers full of water so that they can be returned to service. It involves adding extra chemicals (usually something to increase alkalinity, an oxygen scavenger, and a dispersant) to the boiler water. The water level is raised in the idle boiler to eliminate air spaces, and the boiler is kept completely full of treated water. Superheaters require special protection. Nitrogen gas can also be used on airtight boilers to maintain a positive pressure on the boiler, thereby preventing oxygen in-leakage.

Dry Boiler Lay-Up. This method of lay-up is usually for longer boiler outages. It involves draining, cleaning, and drying the boiler. A material that absorbs moisture, such as hydrated lime or silica gel, is placed in trays inside the boiler. The boiler is then sealed carefully to keep out air. Periodic inspection and replacement of the drying chemical are required during long storage periods.

Steam and Condensate Systems

Two problems associated with steam and condensate systems include general corrosion and pitting corrosion. In order to prevent

condensate corrosion, the systems must be protected from acidic conditions, which lead to general corrosion, and oxygen, which leads to pitting corrosion. Protection can be by mechanical or chemical means or a combination of both. The following methods are commonly used for condensate system protection.

Protection from General Corrosion

Mechanical Protection. Reduce alkalinity from boiler feedwater to minimize the amount of carbon dioxide in the system. Carbon dioxide reacts with water (condensate) and forms carbonic acid that will corrode condensate system metal. Alkalinity can be reduced by dealkalization, demineralization, and reverse osmosis. Note: In many cases mechanical reduction of alkalinity is not needed due to low alkalinity makeup water and/or feedwater.

Chemical Protection. Use volatile amines, such as morpholine, diethylaminoethanol (DEAE), and cyclohexylamine, to neutralize carbonic acid and keep the condensate pH between 8.0 and 9.0.

Protection from Oxygen Corrosion

Mechanical Protection. Reduce oxygen from all boiler feedwater to prevent oxygen carryover to the steam and condensate system (via mechanical methods and chemical oxygen scavengers).

Chemical Protection. Feed filming amines, such as octadecylamine, to the steam to form a thin, hydrophobic film on the condensate system surfaces.

Chemical Protection. Feed a volatile oxygen scavenger to the steam to scavenge the oxygen.

The need for chemical treatment can be reduced by designing and maintaining tight return systems so that the condensate is returned to the boiler and less makeup is required in the boiler feedwater. The greater the amount of makeup, the more the system requires increased chemical treatment.

TERMINOLOGY

The following terms are commonly used in the water treatment industry as they pertain to corrosion, scale formation and fouling.

Alkalinity. The sum of bicarbonate, carbonate, and hydroxide ions in water. Other ions, such as borate, phosphate, or silicate, can also contribute to alkalinity.

Anion. A negatively charged ion of an electrolyte that migrates toward the anode influenced by an electric potential gradient.

Anode. The electrode of an electrolytic cell at which oxidation occurs.

Biological deposits. Water-formed deposits of biological organisms or the products of their life processes, such as barnacles, algae, or slimes.

Cathode. The electrode of an electrolytic cell at which reduction occurs.

Cation. A positively charged ion of an electrolyte that migrates toward the cathode influenced by an electric potential gradient.

Corrosion. The deterioration of a material, usually a metal, by reaction with its environment.

Corrosivity. The capacity of an environment or environmental factor to bring about destruction of a specific metal by the process of corrosion.

Electrolyte. A solution through which an electric current can flow.

Filtration. Process of passing a liquid through a porous material in such a manner as to remove suspended matter from the liquid.

Galvanic corrosion. Corrosion resulting from the contact of two dissimilar metals in an electrolyte or from the contact of two similar metals in an electrolyte of nonuniform concentration.

Hardness. The sum of the calcium and magnesium ions in water; usually expressed in mg/kg as CaCO₃.

Inhibitor. A chemical substance that reduces the rate of corrosion, scale formation, fouling, or slime production.

Ion. An electrically charged atom or group of atoms.

Passivity. The tendency of a metal to become inactive in a given environment.

pH. The logarithm of the reciprocal of the hydrogen ion concentration of a solution. pH values below 7 are increasingly acidic; those above 7 are increasingly alkaline.

Polarization. The deviation from the open circuit potential of an electrode resulting from the passage of current.

ppm. Parts per million by mass. In water, ppm are essentially the same as milligrams per liter (mg/L); 10 000 ppm (mg/L) = 1%.

Scale. 1. The formation at high temperature of thick corrosion product layers on a metal surface. 2. The precipitation of water-insoluble constituents on a surface.

Sludge. A sedimentary water-formed deposit, either of biological origin or suspended particles from the air.

Tuberculation. The formation over a surface of scattered, knob-like mounds of localized corrosion products.

Water-formed deposit. Any accumulation of insoluble material derived from water or formed by the reaction with water on surfaces in contact with it.

REFERENCES

- ABMA. 1995. Boiler water limits and achievable steam purity for water-tube boilers. American Boiler Manufacturers Association, Arlington, VA.
- ASHRAE. 1998. Legionellosis position statement and Legionellosis position paper.
- ASME. 1994. Consensus on operating practices for the control of feedwater and boiler water chemistry in modern industrial boilers. Research Committee on Water in Thermal Power Systems, Industrial Boiler Subcommittee. American Society of Mechanical Engineers, New York.
- DOE. 1998. Non-chemical technologies for scale and hardness control. *Federal Technology Alert* DOE/EE-0162. U.S. Department of Energy. Web site: <http://www.pnl.gov/fta>.
- Gan, F., D.-T. Chin, and A. Meitz. 1996. Laboratory evaluation of ozone as a corrosion inhibitor for carbon steel, copper, and galvanized steel in cooling water. *ASHRAE Transactions* 102(1).
- Graman, P.S., G.A. Quinlan, and J.A. Rank. 1997. Nosocomial legionellosis traced to a contaminated ice machine. *Infection Control and Hospital Epidemiology* 18(9):637-640.
- Langelier, W.F. 1936. The analytical control of anticorrosion water treatment. *Journal of the American Water Works Association* 28:1500.
- Liu, Z., J.E. Stout, L. Tedesco, M. Boldin, C. Hwang, W.F. Diven, and V.L. Yu. 1994. Controlled evaluation of copper-silver ionization in eradicating *Legionella pneumophila* from a hospital water distribution system. *The Journal of Infectious Diseases* 169:919-922.
- Nasrazadani, S. and T.J. Chao. 1996. Laboratory evaluations of ozone as a scale inhibitor for use in open recirculating cooling systems. *ASHRAE Transactions* 102(2).
- Ryznar, J.W. 1944. A new index for determining amount of calcium carbonate scale formed by a water. *Journal of the American Water Works Association* 36:472.