

THE FORMS OF
CORROSION IN COPPER TUBE SYSTEMS
CONVEYING DOMESTIC WATERS

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Introduction

During the past twenty years, Copper Development Association (CDA) personnel have been intimately involved in over 1,200 investigations of copper tube system incidents of corrosion by domestic waters. Based upon these investigations, it can be concluded that the forms of corrosion which can occur when these systems are used to convey domestic waters are:

- (1) soldering flux-induced pitting attack,
- (2) hydrogen sulfide-induced pitting attack,
- (3) erosion-corrosion and its special form cavitation,
- (4) cuprosolvency,
- (5) concentration-cell corrosion,
- (6) chemistry-related cold water pitting, and
- (7) chemistry-related hot water pitting.

It should be appreciated that combinations of these corrosion forms can occur concurrently wherein the synergistic deleterious effects can be especially damaging.

CDA personnel have an enviable historical record with regards to making recommendations for viably and cost effectively mitigating copper water tube system corrosion. This is understandable because the priority of each CDA corrosion investigation is to correctly identify the form(s) of corrosion involved. Typically, each investigation includes energy dispersive spectroscopy (EDS), scanning electron microscopy (SEM) and microchemical analysis (MCA) of the corrosion products and the adversely affected areas along with a thorough review of the background history (esp., with regards to water chemistry) of the piping system.

Once the form(s) of corrosion has been correctly identified and its basic cause(s) established, readily available techniques can be used to prevent recurrence of the deterioration. These techniques include proper system design, installation of the system using industry-standard materials and workmanship, operation of the system within its design parameters, and proper water treatment. The mitigation techniques, however, are not universal; they cannot be applied without fully understanding why the corrosion occurred. For example, the technique most commonly used to mitigate the chemistry-related cold water pitting of copper is not a viable option for mitigating hydrogen sulfide-induced pitting attack; erosion-corrosion is not eliminated using the same approach as that used to eliminate concentration-cell corrosion.

With regards to predicting corrosion and the application of corrosion-control techniques for copper tubes and fittings exposed to domestic waters, it must be appreciated that the widely used indices (i.e., the Langelier, Ryznar, saturation, and stability indices) are not applicable. Copper will behave as a noble metal as long as its naturally protective tarnish film of cuprous oxide (Cu_2O) remains intact. It does not require the deposition of calcium carbonate (CaCO_3) scale on the waterside surfaces for effective corrosion control.

Soldering Flux-Induced Pitting Attack^{1 (1)}

Soldering flux-induced pitting attack is almost always associated with the use of an unusually aggressive flux and/or the application of excessive amounts of flux. Once initiated at the flux-activated sites, propagation of the pits is facilitated by the natural presence of dissolved oxygen in the water conveyed. Most often, flux-induced pitting occurs preferentially in cold-water lines; it is also known to occur in infrequently used hot water lines.

Flux-induced pits contain porous, reddish-brown cuprous oxide, with the pits being covered with relatively voluminous, friable tubercles of greenish-colored, copper corrosion products (Figure 1). Typically, the tubercles consist of basic copper carbonate (i.e., malachite) and/or copper chloride(s). The pits are not normally randomly occurring; they tend to occur preferentially along relatively narrow bands that are nearly parallel to the longitudinal axes of the tubes and fittings (i.e., along the "ghosts" of flux runs). Often, the bands/band of pits in these areas are covered with tubercle ridges (e.g., see top tube half-section in Figure 1) rather than distinct, hemispherically shaped, individual tubercles. Flux-induced pits also occur preferentially on the periphery of the sticky, petrolatum-base flux residues/runs, which often exist on the waterside surfaces when the plumbing technician applies excessive flux. When the latter is observed, it is not uncommon to also find globules of solder on the waterside surfaces of the tubes and fittings. Although flux-induced pitting can be expected to occur at or in the near vicinity of soldered connections associated with poor workmanship, cases are known where the pitting occurred over eight feet away from a fitting.

Soldering flux-induced pitting can be confirmed using energy dispersive spectroscopy. Chlorides in major amounts, and sometimes zinc, will be detected in the pits or on the edges of the pits (Figure 2). Copper chloride(s) coexists with the porous cuprous oxide at the pit sites. The latter is understandable because soldering fluxes commonly contain activating chlorides such as ammonium chloride, zinc chloride, tin chloride and/or hydrochloric acid.

⁽¹⁾ Numbers in parentheses refer to footnotes; numbers without parentheses are references.

Soldering flux-induced pitting can be effectively mitigated by requiring plumbing technicians to use industry-standard materials and workmanship when installing copper tube systems. Fluxes used for soldering copper water tube systems should satisfy the requirements of American Society for Testing and Materials (ASTM) Standard Specification B813² and soldered connections must be made in accordance with the guidelines presented in ASTM Standard Practice B828³ and the CDA Copper Tube Handbook.



Figure 1 – The soldering flux-induced pits were covered with friable, greenish-colored tubercles of copper corrosion products. The perforations through the tube walls (i.e., see arrows) and most of the pits existed along relatively narrow bands, which were nearly parallel to the longitudinal axes of the tubes (i.e., along the “ghosts” of flux runs).

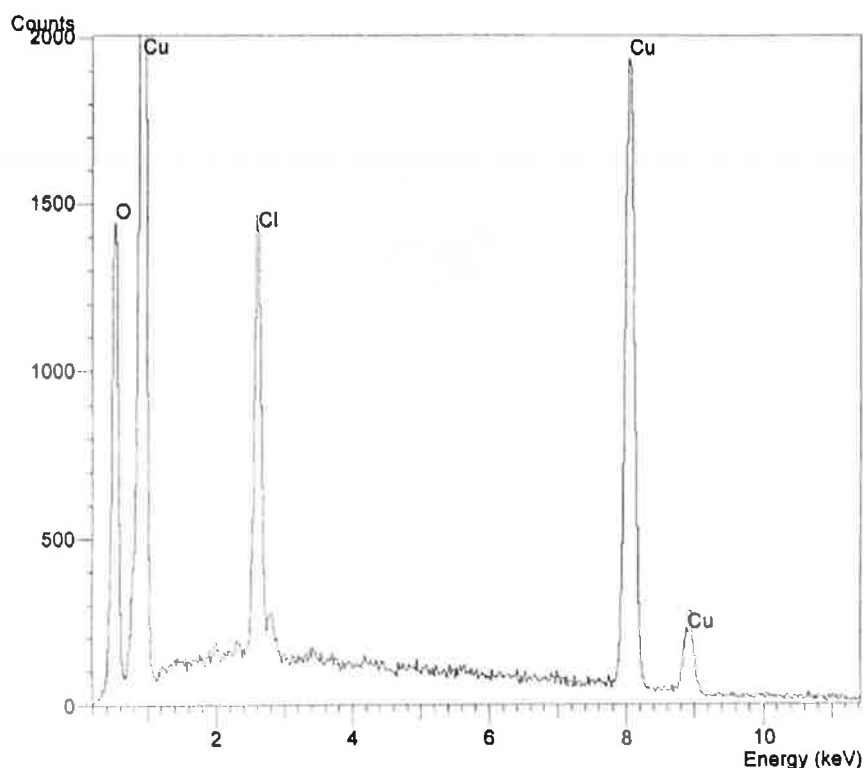


Figure 2 - Energy dispersive spectroscopy normally reveals the presence of major amounts of chloride at the pit sites when the localized attack is soldering flux-induced.

Hydrogen Sulfide-Induced Pitting Attack

Very small quantities of dissolved hydrogen sulfide (H_2S) in water can cause unacceptable pitting of many metallic materials used to convey domestic waters, including copper and many of its alloys. The threshold concentration above which hydrogen sulfide-induced pitting of copper can be expected to occur is not precisely known. It is known that quantities as low as 0.020 milligram per liter (mg/l) have resulted in copper tube and fitting perforations.

Typically, hydrogen sulfide-containing domestic waters are obtained from well supplies. The sulfide is a natural constituent in the well water, resulting from underground, sulfate-reducing-bacteria (SRB) activity and/or general bacteria decomposition. A fairly large number of these well supplies are known to exist in the states of Alabama, Georgia, and Florida. For example, in Florida, the Ocala Aquifer reportedly contains appreciable amounts of sulfide.⁴ It is also known that SRB activity exists in many of the mains and lines used to distribute domestic waters.

Hydrogen sulfide-induced pitting is randomly occurring on the waterside surfaces of the copper tubes and fittings (Figure 3). The corrosion-induced pits typically contain porous, dark, reddish-brown to nearly black cuprous oxide; the pits are normally overlaid with friable, greenish-colored tubercles of copper corrosion products. The tubercles most often consist primarily of copper sulfate that is sometimes admixed with some black, copper sulfide(s). Regardless of the tubercle composition, black, loosely adherent and porous layers of copper sulfide(s) are always associated with the pitting attack. The presence of these corrosion products can be readily verified using EDS and MCA.

Hydrogen sulfide can be effectively removed from water supplies at the treatment plant by a number of techniques.^{4,5} For example, it has been successfully accomplished by reducing the pH of the well water followed by aeration in a forced-draft tower(s). Aeration removes the sulfide by the scrubbing action of the air and by oxidation. Lowering the pH of the water greatly reduces the size of the aerating equipment required.

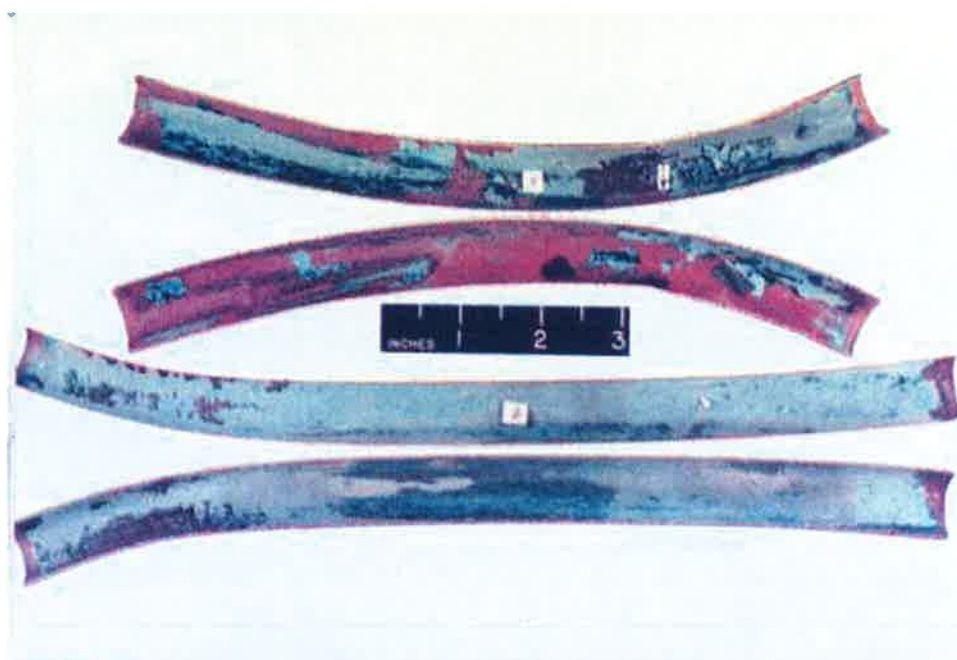


Figure 3 - Hydrogen sulfide-induced pits are typically overlaid with friable, greenish-colored to blackish tubercles of copper corrosion products. Loosely adherent and porous layers of copper sulfide(s) are associated with the pitting attack (e.g., see upper two tube half-sections where these products had, in part, broken loose).

Erosion-Corrosion⁶⁻⁸

Erosion-corrosion of copper tubes and fittings (i.e., accelerated attack related to localized, high-velocity/turbulent water inside the tubes and fittings) is normally associated with circulating, domestic hot water systems. Approximately 95% of all erosion-corrosion concerns investigated occurred in circulating, hot water tubes and fittings.

When erosion-corrosion occurs in cold-water lines, the cause is almost always an unusually high water pressure (i.e., a pressure much greater than about 80 pounds per square inch gauge (psig), high water velocity often in excess of 7 – 8 feet per second (fps), and/or poor workmanship when the system was installed. With regards to the latter, erosion-corrosion has been associated with unreamed cut-tube ends, globules of solder on the waterside surfaces, dents in the tubes and fittings, tubes which were not fully inserted into fittings prior to soldering, tubes which were "cocked" in fittings, tubes which were not squarely cut, improperly-installed flared-tube fittings, and other locations where smooth flow had been disrupted and excessive turbulence exists. Of the workmanship-related causes of erosion-corrosion, the most serious and most prevalent is the failure to ream cut-tube ends. These same workmanship-related installation practices also promote and facilitate erosion-corrosion in circulating, hot water systems.

Erosion-corrosion can be readily recognized (Figure 4). The areas of attack are typically grooved and essentially free of residual corrosion products; the affected areas are normally bright and shiny like a new U.S. penny. This is understandable because the erosion phase of the rapidly repetitive, erosion-corrosion process removes the copper oxide(s) films from the copper surfaces. Often, the U-shaped pits in the areas of attack are sufficiently distinct that the direction of former water flow can be determined. When looking down on the surface, the orientation of the attack (i.e., the U-shaped pits) is such that it gives the impression of "horses walking upstream." Lengthwise sections taken through areas of erosion-corrosion will normally reveal undercutting which has the appearance of ocean waves wherein the wave crests face the direction of former water flow.⁷

In circulating, hot water systems, erosion-corrosion is often associated with naturally soft waters or waters which have been softened to a near-zero hardness, especially if the waters contain appreciable amounts of dissolved oxygen and/or dissolved carbon dioxide. Erosion-corrosion is further facilitated by water temperatures greater than about 140°F and flow rates above about 4 to 5 feet per second (fps). Erosion-corrosion can be especially severe at water temperatures greater than about 160°F where black cupric oxide (CuO) forms on the copper tube and fitting surfaces instead of cuprous oxide. Apparently, cupric oxide is much less resistant to erosion-corrosion than cuprous oxide. Cases are also known where the erosion-corrosion process was facilitated by the presence of abrasive suspended solids (e.g., iron oxide and/or sand) in the circulating water. Often, the erosion-corrosion damage is restricted to locations where the water flow makes multiple changes in direction over relatively short distances.

Erosion-corrosion in cold-water systems can be effectively mitigated by insuring that the water pressure does not exceed about 80 psig and water velocities do not exceed the industry recommended 8 fps. Concurrently, plumbing technicians must use industry-standard workmanship when installing these systems.³

Erosion-corrosion in domestic hot-water systems can be effectively mitigated by insuring that, in addition to those requirements for the installation and operation of cold-water systems, the water velocity does not exceed about 4 to 5 fps,⁽²⁾ the water temperature is maintained at a safe and energy-efficient 120 to 130°F, and unacceptable amounts of abrasive suspended solids do not exist in the circulating water.⁸ With regards to the latter, the source of abrasive iron oxide(s) in the water is often the corrosion of steel, hot-water heaters/storage tanks upstream of the copper tube systems (i.e., a condition which can usually be corrected by properly selected and applied protective coatings, generally in conjunction with cathodic protection).

In systems where water must be circulated at temperatures greater than 120 to 130°F, such as in radiant heating systems, water velocities should be controlled below the recommended 4 – 5 fps, such as at 2 – 3 fps. Where velocities are required to exceed 4 – 5 fps, or aggressive domestic waters must be circulated consideration should be given to the selection of 90 copper-10 nickel (i.e., Copper Alloy No. C70600) tubes and fittings.⁸

Cavitation, a special form of erosion-corrosion, can occur in domestic water systems if the system hydrodynamics are such that they allow vapor/gaseous bubbles to form at low pressure which are subsequently collapsed/imploded at high pressure. Bubble implosion, which produces very high localized pressures (shock waves) destroys the copper's protective tarnish film and creates boundary layer water temperatures which are much higher than that of the water being conveyed. Typically, cavitated copper can be recognized by the absence of residual corrosion products in the affected areas and the presence of bright copper and sponge-like rounded pits (Figure 5).

Cavitation concerns in copper water tube systems can be most effectively mitigated by changing the system design so as to minimize hydrodynamic pressure differences associated with the flow of water.

⁽²⁾ Excessive velocity in circulating systems is often associated with an oversized circulating pump(s) and/or undersized tubes and fittings. Sometimes these conditions result from a design deficiency or when the original design was altered during installation of the system.



Figure 4 - The U-shaped pits and associated perforations through the tube wall (i.e., see arrows) in the localized, corrosion product free area of erosion-corrosion were sufficiently distinct that the direction of former hot water flow could be determined.

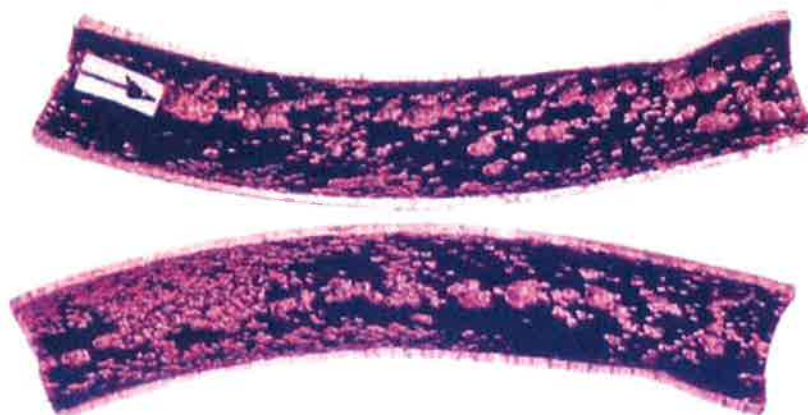


Figure 5 - The perforation through the tube wall (i.e., see arrow) existed in a localized area of severe cavitation. Surface heating by the cavitation process caused the formation of black cupric oxide on the copper where cavitation had not occurred in the cold water line.

Cuprosolvency⁹⁻¹¹

Cuprosolvency, sometimes referred to as the "blue/green" water concern, describes the slow, general corrosion (i.e., uniform attack) of copper water tubes and fittings by certain domestic waters. The concern with cuprosolvency is that it can result in somewhat elevated copper contents in the water following periods of zero flow (e.g., the first water drawn in the morning may have a higher than normal copper content) and stained plumbing fixtures. Occasionally, it is reported that some "blondes" shampooing in a cuprosolvent water observe that their hair becomes somewhat green. Ironically, cuprosolvent waters and the "green-hair" connection is apparently not a concern for natural blondes. Although a cuprosolvent water can be somewhat annoying, there are no known incidents where it culminated in a perforation through a tube or fitting wall.

Cuprosolvency occurs because the waterside surfaces of the copper tubes and fittings do not form or completely form their naturally protective tarnish film of cuprous oxide. Rather, the copper surfaces develop a thin, loosely-adherent, flocculent-type, layer of bluish to bluish-green colored, copper corrosion products which typically include copper hydroxide (Figure 6).¹¹ Formed during periods of water stagnation, it is the removal of these products by water flow that creates the cuprosolvency concern.

Cuprosolvent waters typically are very soft (e.g., waters which have been softened to a near-zero hardness); they normally have a pH of less than seven and a low alkalinity. In general, the pHs of these waters are less than neutral because they contain appreciable amounts of dissolved carbon dioxide⁹

The vast majority of bluish/greenish-colored water concerns are self-correcting. Once a sufficient amount of water and its associated dissolved oxygen has flowed through the lines, the concern disappears because the copper, in time, forms its naturally protective tarnish film of cuprous oxide. In persistent situations, cuprosolvency can be corrected by raising the pH of the water to about 8 through additions of chemicals such as sodium hydroxide (NaOH) or calcium hydroxide, Ca(OH)₂. Cuprosolvency can often be corrected at individual residences by the installation of neutralizing filters.

Cases are known, however, where the cuprosolvency was soldering flux induced. Instead of developing corrosion-induced pits, the flux causes the slow, nearly uniform dissolution of copper. Water treatment has not been known to be of any significant benefit in mitigating the cuprosolvency concern in these incidents.

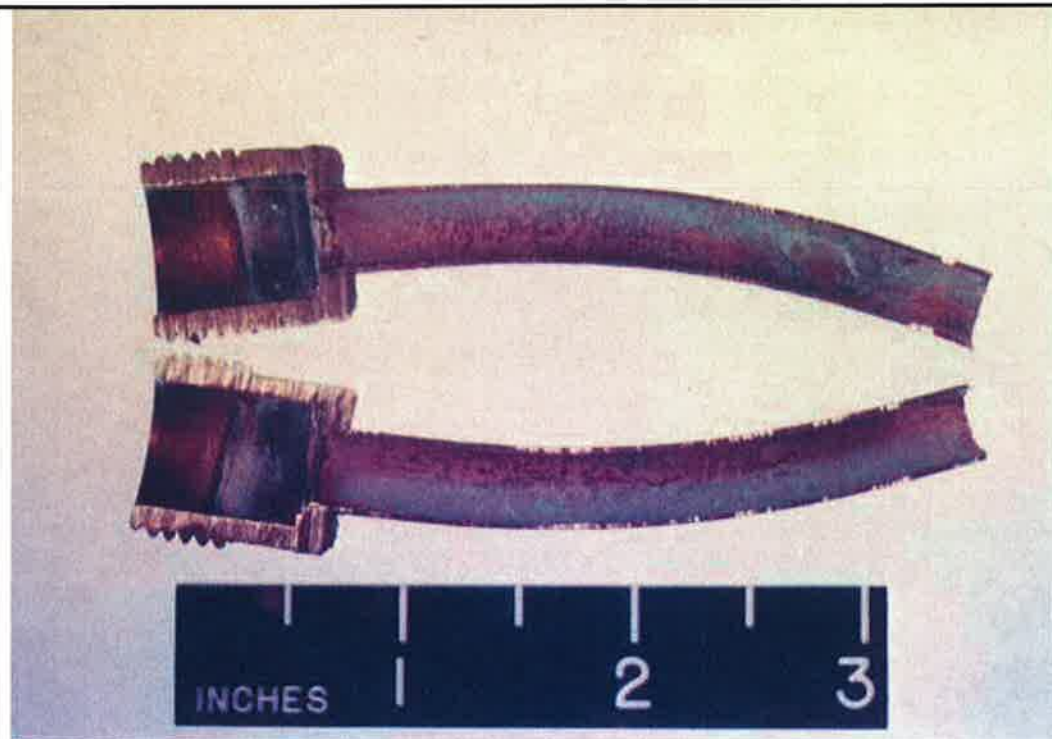


Figure 6 - A loosely adherent, flocculent-type layer of bluish tinted copper corrosion products existed on the waterside surface of the tube. The cuprosolvency was clearly evident to be associated with failure of the copper water tube to completely passivate (e.g., see speckled appearance of the copper tube surface).

Concentration-Cell Corrosion^{12,13}

Although at least five forms of concentration-cell corrosion are known to exist,¹³ the form associated with copper, domestic water systems is the oxygen-differential type of attack. It is often referred to as underdeposit corrosion because the deterioration occurs preferentially in the form of pits under deposits, or the thicker layers of deposits, where the oxygen content of the water is low relative to that of the water immediately adjacent to the deposits. In this regard, it should be appreciated that all domestic waters contain dissolved oxygen.

The localized, corrosion process can be especially rapid, for example, when chloride anions migrate to the anodic sites under the deposits and react with metal cations to form metal chlorides, which subsequently hydrolyze to form hydrochloric acid.

The source of the deposits on tubes and fittings is almost always suspended solids in the water conveyed. Often, they consist of iron oxide(s) and/or silica/sand (Figure 7). It is not at all unusual for the source of the iron oxide(s) to be the corrosion of cast-

iron/ductile-iron mains used to distribute the water or the galvanized-steel service lines used to connect buildings with the mains. Iron oxide(s) can also result from the oxidation of natural constituents in the water (e.g., iron bicarbonate). The normal cause when the deposits consist primarily of silica/sand is over-pumping a well(s) or a deteriorating concrete or cement-lined water main. Cases are known where the source of the deposits was the post-precipitation of colloids leaving the water treatment plant (e.g., where the coagulation and settling times and/or the filtration process used to clarify turbid water were inadequate).

Once the source of the corrosion-causing deposits is positively identified, suspended solids in water can normally be effectively eliminated. For example, the corrosion of cast-iron/ductile-iron mains and galvanized-steel service lines can be viably and cost-effectively mitigated by proper water treatment,¹² normally by the water purveyor. It is also well established that suspended solids in water can be removed by filtration,¹² either at the treatment plant or the affected building/residence and that improved dwell time at the treatment plant can help eliminate the post-precipitation of suspended solids in the water distribution system.

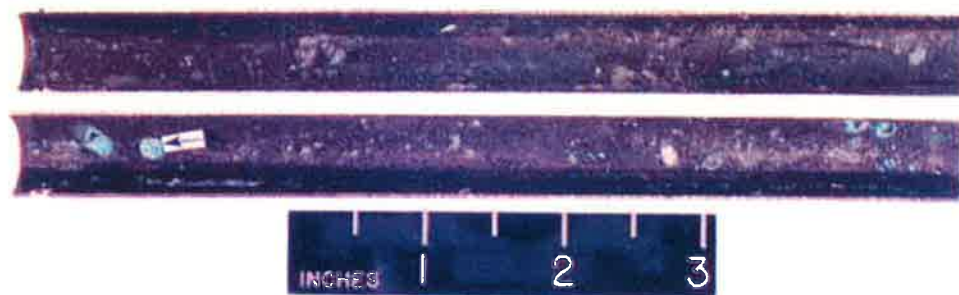


Figure 7 - Concentration-cell corrosion in the form of pitting attack had occurred preferentially under the thicker layers of hydrated hematite (Fe_2O_3) and silica (SiO_2) deposits on the waterside surface of the cold water line. The perforation through the tube wall (i.e., see arrow) was covered with a friable tubercle of greenish-colored copper corrosion products.

Chemistry-Related Cold Water Pitting^{9,14-17}

Chemistry-related cold-water pitting of copper tubes and fittings, sometimes referred to as nodular pitting and/or Type 1 pitting, is associated with certain, aggressive well waters or combinations of well and surface supplies. Normally, the pitting only occurs in cold-water lines or infrequently used hot-water lines.

The randomly occurring corrosion-induced pits associated with the pitting attack contain porous, reddish-brown cuprous oxide, with the pits being overlaid with discrete, friable, relatively voluminous tubercles of greenish-colored copper corrosion products (Figure 8). Typically, EDS and MCA reveal that the tubercles consist primarily of basic copper carbonate.¹⁵ EDS will sometimes show that copper chloride(s) coexists with the porous, cuprous oxide in the pits. Where localized pitting has not occurred, there will be no significant deterioration by the water conveyed. Basically, the copper in these essentially unaffected areas will be covered with a protective tarnish film of cuprous oxide which, in general, will be overlaid with a thin layer of greenish-colored deposits from the water (i.e., typically malachite), the source of which is the pitting of copper upstream in the system.

Chemistry-related cold-water pitting can be readily distinguished from flux-induced pitting (i.e., another form of pitting associated with cold-water lines or infrequently used hot-water tubes and fittings) by the randomness of its occurrence. The pitting is not located preferentially along the "ghosts" of flux runs or on the periphery of sticky, petrolatum-base, flux residues.

Waters which are commonly associated with this form of pitting attack normally have a pH in the range of 7.0 to 7.7 and contain more than about 25 mg/l dissolved carbon dioxide along with dissolved oxygen. Often the water will contain more than about 15 mg/l chloride and over 17 mg/l sulfate, with the sulfate-to-chloride ratio often in excess of about 3. Based on better than 100 investigations regarding the chemistry-related cold-water pitting of copper tubes and fittings, there is no reason to believe that any manufacturing-related carbon films or other deleterious films on the copper surfaces are a factor in the pitting attack.¹⁵ This is understandable because chemistry-related cold-water pitting, in those relatively-rare instances when it does occur, can be effectively mitigated by slightly changing the water's chemistry.

The most viable and cost-effective solution to overcoming chemistry-related cold-water pitting in copper domestic water systems is to reduce the dissolved carbon dioxide content of the offending water to a sufficiently-low level.¹⁴⁻¹⁷ Raising a water's pH to about 8 while concurrently reducing its carbon dioxide content to less than about 5 mg/l will successfully mitigate the concern. Environmentally acceptable chemical additions for achieving this objective include caustic soda, lime, and soda ash. These are usually added to the offending water at the treatment plant. For a private residence, the same objective usually can be achieved by the installation of a neutralizing filter.



Figure 8 - Randomly-occurring, tubercle-covered corrosion-induced pits (e.g., see arrow where a perforation through the tube wall existed) existed on the waterside surface of the tube which had conveyed a domestic cold water containing appreciable amounts of dissolved carbon dioxide in conjunction with dissolved oxygen.

Chemistry-Related Hot-Water Pitting^{18, 19}

Domestic hot waters containing relatively small amounts of iron, manganese, and/or aluminum have been associated with the hot water pitting of copper tubes and fittings. There is also reason to believe that, when the hot water pitting occurs, a silicon-containing constituent could be involved. With regards to the threshold quantities of aluminum, manganese, and iron required to initiate the pitting attack, they are suspected of being as low as, respectively, 0.10,¹⁸ 0.03,¹⁹ and 0.10 mg/l. Generally, hot water pitting associated with the presence of these metals in the water is a concern when the water has been heated to temperatures in excess of about 160°F and black, cupric oxide exists on the hot, copper surfaces.

Typically, the corrosion-induced pits will contain porous, reddish-brown cuprous oxide and be covered with friable, relatively voluminous tubercles of greenish-colored copper corrosion products (Figure 9). EDS and MCA almost always reveal that the tubercles consist primarily of copper sulfate. Often, small amounts of the pit-initiating metal will be detected during EDS of the tubercles. It is unusual for EDS to detect any chloride-containing products in the pits.

Where pitting has not occurred and the copper is covered with a thin layer of cupric oxide, it is common to observe friable, loosely adherent layer of brownish-colored (Figure 10) or brownish-black colored deposits from the water (Figure 9). EDS of these products in the immediate vicinity of the pits will provide the insight required to identify the offending metal(s), which is primarily responsible for the pitting attack. The deposits will contain varying amounts of aluminum, iron, and/or manganese.

Briefly, iron and manganese appear to initiate the pitting attack by the deposition of, respectively, highly cathodic iron oxide (esp., hydrated hematite) and highly cathodic manganese dioxide (MnO_2) on the hot, copper surfaces, especially at locations where temporary defects in the copper oxide layer might exist. Once initiated, the pits will propagate by microgalvanic corrosion and concentration-cell corrosion of the oxygen-differential form. The role of aluminum in the hot-water pitting process (Figure 9) is somewhat less clear because the only investigators on the subject were interested in solving a practical concern, not providing fundamental research.¹⁸ The pitting process could involve the deposition and subsequent hydrolysis of aluminum sulfate to aluminum hydroxide on the hot, copper surfaces which could cause the localized destruction of the copper's passive film.

Regardless of the corrosion mechanisms associated with the copper pitting by waters containing iron, manganese, and/or aluminum, the phenomena is clearly facilitated by heating the waters conveyed to higher-than-necessary temperatures and by the presence of sulfate in the waters.

Hot water pitting by manganese and/or iron-containing waters can often be mitigated by reducing the concentration of these constituents in the waters to acceptable levels at the treatment plant. Iron and manganese-removal systems are available to accomplish this objective. For example, colloidal iron can be removed by coagulation, flocculation and precipitation or filtration. Sometimes the iron content of a water can be sufficiently reduced by, for example, mitigating the corrosion of hot-water heaters/storage tanks, cast-iron/ductile-iron mains, and/or galvanized-steel service lines upstream of the copper tube system. Cases are also known where the hot water pitting was effectively mitigated by reducing the temperature of the water to a safe and energy efficient 120 to 130°F. Properly blended sodium silicate – organic polyphosphate inhibitors added to the water have also been known to mitigate the corrosion concern.

The hot-water pitting associated with the presence of aluminum in the water has been effectively mitigated by raising the pH of the water to about 8.5 while reducing the aluminum content to less than about 0.1 mg/l. Often, the aluminum content of a water, as well as its sulfate content, can be reduced to an acceptable level by simply reducing the amount of aluminum sulfate used for coagulation at the treatment plant and/or insuring adequate coagulation, settling, and filtering of the water before it is distributed. Reducing the temperature of the hot water from 165°F to 130°F has also been known to correct the pitting concern. Recent studies also suggest that the aluminum contents of domestic hot waters can be reduced to acceptable levels by avoiding the use of sacrificial aluminum-alloy anodes in the hot water heaters.



Figure 9 - The pits were covered with friable tubercles of greenish-colored copper corrosion products. Loosely-adherent layers of brownish-colored hydrated hematite deposits covered the black cupric oxide which existed on the waterside surface of the hot water line.

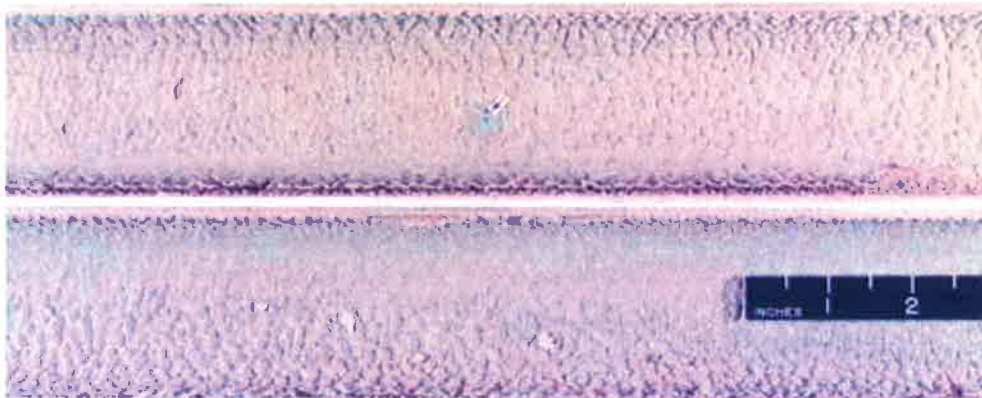


Figure 10 - The perforation through the tube wall (i.e., see arrow) was covered with a friable tubercle of greenish-colored copper corrosion products. In general, the cupric oxide on the copper tube surface was covered with a relatively-thick, loosely-adherent layer of brownish-colored deposits from the hot water conveyed. EDS revealed that the brownish-colored products contained significant amounts of aluminum.

Conclusions

Based upon the CDA experience regarding the corrosion of copper tubes and fittings by domestic waters, it can be concluded that the seven basic forms of waterside corrosion can be viably and cost effectively mitigated providing the water purveyors distribute quality products (e.g., waters which do not contain unacceptable amounts of suspended solids, dissolved carbon dioxide, manganese, aluminum, dissolved hydrogen sulfide and/or iron), the copper tube systems are properly designed (e.g., for circulating systems, the velocities do not exceed about 4 to 5 fps), the copper tube systems are properly installed (e.g., the systems are installed using the general guidelines presented in ASTM Standard Specification B828 and the CDA Copper Tube Handbook without the use of excessive flux and the use of unusually-aggressive fluxes), and the copper tube systems are operated within the design parameters (e.g., domestic hot-water temperatures do not exceed a safe and energy-efficient 120 to 130°F and measures are taken to prevent the corrosion of water heaters/storage tanks).