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REVIEW ARTICLE

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Examining the efficacy of copper-silver ionization for management of *Legionella*: Recommendations for optimal use

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Abstract

Although copper-silver ionization (CSI) has been used for 30 years to inactivate *Legionella* bacteria and other opportunistic pathogens in water, the literature is a mix of both successes and failures. This paper reviews the technology and case studies to help improve the success of CSI installations. Important is a properly designed system capable of consistent delivery of copper/silver ions at their target levels. However, even the most advanced system will fail if not properly operated and maintained. Water chemistry can impact the performance of CSI systems and attention should be on conductivity, temperature, oxygen, flow, pH, chloride, sulfate, alkalinity, hardness, phosphate and dissolved organic carbon levels. Several case studies are provided to demonstrate the effectiveness of CSI treatment even at high pH levels. The report concludes that the use of CSI to control *Legionella* and other opportunistic pathogens is highly effective when the units are properly designed, maintained, and operated.

KEYWORDS

copper, ionization, *Legionella*, Legionnaires disease, silver, water treatment

1 | INTRODUCTION

The incidence of Legionnaires' disease has increased nearly 10-fold since the year 2000 and is now the most common pathogen isolated in cases of drinking water-borne disease outbreaks in the United States (Benedict et al., 2017; CDC, 2022), and the most commonly reported cause of water-borne infection in drinking water (Beer et al., 2015). *Legionella* has been responsible for about two-thirds of all drinking water outbreaks (Benedict et al., 2017; CDC, 2022). *L. pneumophila* is the primary cause of Legionnaires' disease, with serogroup 1 accounting for around 95% of U.S. cases. (Yu et al., 2002). During the 2013–2014 reporting period, *Legionella* infections were responsible for all reported deaths due to drinking water-associated disease. Historically outbreaks of Legionnaires' Disease were associated with cooling towers, but more recently the plumbing in large buildings such as hospitals, long-term care facilities, nursing homes, hotels and resorts, and office buildings have been associated with outbreaks (Fitzhenry et al., 2017; Garrison et al., 2016).

There are a variety of options for managing *Legionella* occurrence in building plumbing systems, and these options should be considered and implemented through the development of a comprehensive water management

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program (ASHREA, 2018; CDC, 2022). An important "rule of thumb" is to "keep the hot water hot, the cold water cold, and avoid water stagnation." To supplement treatment within building plumbing systems, the application of copper-silver (Cu-Ag) ionization (termed CSI) to control *Legionella* in building water systems is widespread, partly because of its relatively low cost, minimal impact on plumbing, low maintenance compared to other control processes, few by-product reactions, and limited regulatory implications.

The use of silver ionization for water disinfection was developed by the National Aeronautics and Space Administration (NASA) for the Apollo spacecraft drinking water and wastewater systems (Albright et al., 1967). The combined use of copper and silver ions for water treatment initially focused on the disinfection of swimming pools (Yahya et al., 1989) as an alternative to using high levels of chlorine. Liu et al. (1994) first reported on the effective use of CSI treatment for controlling *Legionella* in hospital water systems, specifically for *L. pneumophila*. CSI systems are currently used in a variety of buildings with complex water systems to control the growth and occurrence of *Legionella* bacteria (USEPA, 2016).

However, a review of the literature of published case studies on CSI applications reveals a mixture of successes and failures. To understand how CSI can be effectively used for the management of *Legionella* and other waterborne pathogens, it is important to understand how to optimize CSI design and application. The fundamental key to CSI's effectiveness is the ability to identify and respond to normal fluctuations in water usage patterns and water chemistry. This is central to CSI efficacy because:

- Municipal water delivered to buildings, particularly in systems with a blend of surface and ground water supply, can fluctuate in water chemistry.
- Water disruptions due to aging water delivery infrastructure, weather, maintenance, and changes in flow can impact the water quality fed from municipal supplies to building plumbing systems.
- Water characteristics are different based on geography and climate.
- Water quality and characteristics within a building's premise plumbing system can change based on infrastructure wear and degradation, heating, stagnation, and pipe characteristics.
- Facility water disruptions can occur due to maintenance and replacement of water-bearing equipment.

This paper will review existing research and literature highlighting the impact of CSI system design, maintenance and operations, and water chemistry on CSI performance for *Legionella* control. This paper will address these water quality and operational characteristics that must be properly addressed to assure that the highest disinfection efficacy is obtained through copper-silver ionization.

Article Impact Statement

Tools to manage *Legionella* are limited and this review provides guidance on how to effectively apply copper-silver ionization in building water systems.

2 | LITERATURE REVIEW METHODS AND CASE STUDY DATA

A search of the relevant literature was performed using the Microsoft Bing and Google Chrome Scholar search engines. Search terms included combinations of the following: "*Legionella*," "copper," "silver," "ionization," "CSI," "disinfection," "resistance," and "regulations." A number of excellent reviews also served as a starting point for background information (Cachafeiro et al., 2007; June & Dziewulski, 2018; Lin et al., 2011; Sicairos-Ruelas et al., 2019; USEPA, 2016). Discussions with a number of colleagues were also helpful, including experts at LiquiTech, Lombard, IL (www.liquitech.com) who provided access to their case study data.

3 | MECHANISMS FOR SILVER DISINFECTION

Silver ions have the highest level of antimicrobial activity of all the metals (Silvestry-Rodriguez et al., 2007). The antibacterial mode of action of silver ions (Davies & Etris, 1997; Kędziora et al., 2018) is connected with:

1. Cell membrane pore formation and leakage of metabolites and ions
2. Denaturation of structural and cytoplasmic proteins; inactivation of enzymes
3. Inactivation of respiratory chain enzymes
4. Increase of intracellular reactive oxygen species (ROS), and
5. Interactions with ribosomes affecting protein synthesis.

The interaction of the silver ions with the bacterial inner membrane is one of the most important mechanisms of microbial inactivation (Kędziora et al., 2018). It has been shown that silver ions will interact with components of the cytoplasm, proteins, and nucleic acids within 30 min of exposure (Jung et al., 2008; Yamanaka et al., 2005). The antibacterial activity of silver ions is directly proportional to the environmental concentration of silver ions, although Lin et al. (1996) reported that silver treatment alone required more than 24 h to achieve 6-log reduction *L. pneumophila* inactivation even at the highest concentrations examined (0.08 mg/L) (Figure 1).

4 | MECHANISMS FOR COPPER DISINFECTION

Copper (and silver) were recognized by the U.S. Environmental Protection Agency (USEPA) as metallic antimicrobial agents in 2008 (https://www.epa.gov/pesticide-registration/pesticide-registration-clarification-ion-generating-equipment). Copper ions interact with negatively charged cell walls of *Legionella* species (and other bacteria), disrupting cell wall permeability and subsequent nutrient uptake. Copper inhibits the respiratory chain on the bacterial membrane which generates free oxidative radicals that ultimately cause lipid peroxidation of cellular membranes, direct oxidation of proteins, and the inactivation of DNA and RNA (Sicairos-Ruelas et al., 2019). At higher temperatures, copper–DNA complexes become stronger, overcoming the naturally attractive forces of DNA strands initiating unwinding and denaturation (Thurman & Gerba, 1989; Warnes et al., 2010). Copper is an essential micronutrient and plays a role in enzymatic functions such as superoxide dismutase and cytochrome oxidase. Cellular levels of copper are carefully regulated and controlled; however, a large enough dose can result in cellular toxicity (Rensing et al., 1999).

Copper alone requires significantly less time for *Legionella* inactivation than silver, (e.g., 2.5 h for a 6-log reduction), although it requires a higher concentration (0.1 mg/L) (Figure 2). Lin et al. (1996) identified an activity threshold of 0.4 mg/L beyond which excess copper concentrations yield no added benefit. However, it is important to note that laboratory studies of copper/silver inactivation may differ from field results where complexation of the metals can occur from natural organic carbon, phosphate corrosion inhibitors, carbonates, and other physicochemical characteristics.

5 | SYNERGIES FOR COPPER-SILVER DISINFECTION

Liu et al. (1994) reported that a combined treatment with copper and silver was associated with a decreased incidence of culturable *Legionella*, and that copper concentrations greater than 0.4 mg/L and silver concentrations greater than 0.04 mg/L had the best performance. Lin et al. (1996) showed that combined CSI reduced the concentration of *L. pneumophila* faster than either copper or silver alone with a 6-log inactivation within 1.6 h. The copper ions form electrostatic compounds with negatively charged cell walls of *Legionella* sp. (and other bacteria), disrupting cell wall permeability and subsequent nutrient uptake. The copper ions penetrate the cell wall and create an entrance for silver ions which penetrate the cells and bond with DNA, RNA, cellular proteins, and respiratory enzymes, immobilizing the cell and curtailing cell division. This chain of events leads to death. Thus, while combining both metal ions have a synergistic effect, the concentration of silver is most important as it is the cause of cell death.

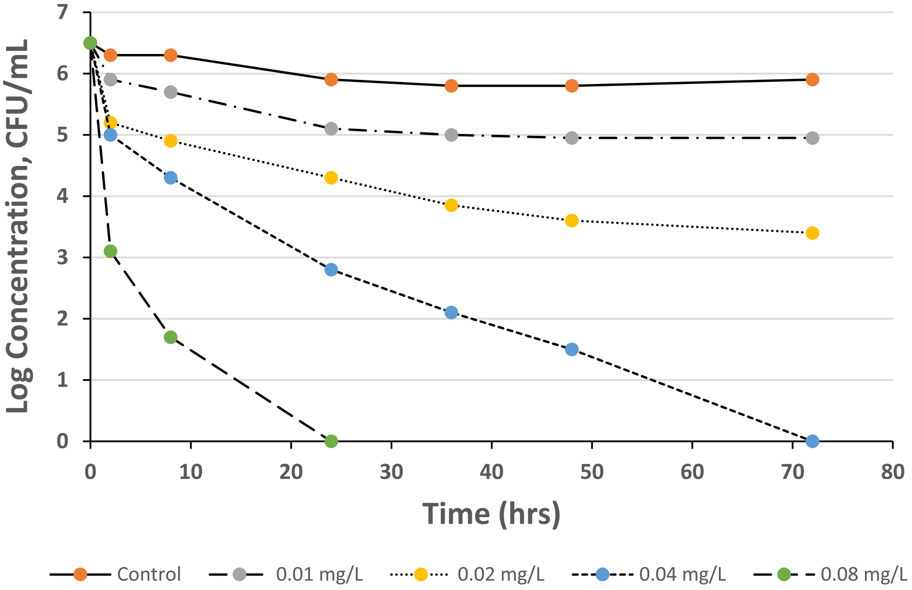


FIGURE 1 Silver inactivation of *L. pneumophila*. Adapted from Lin et al., 1996.

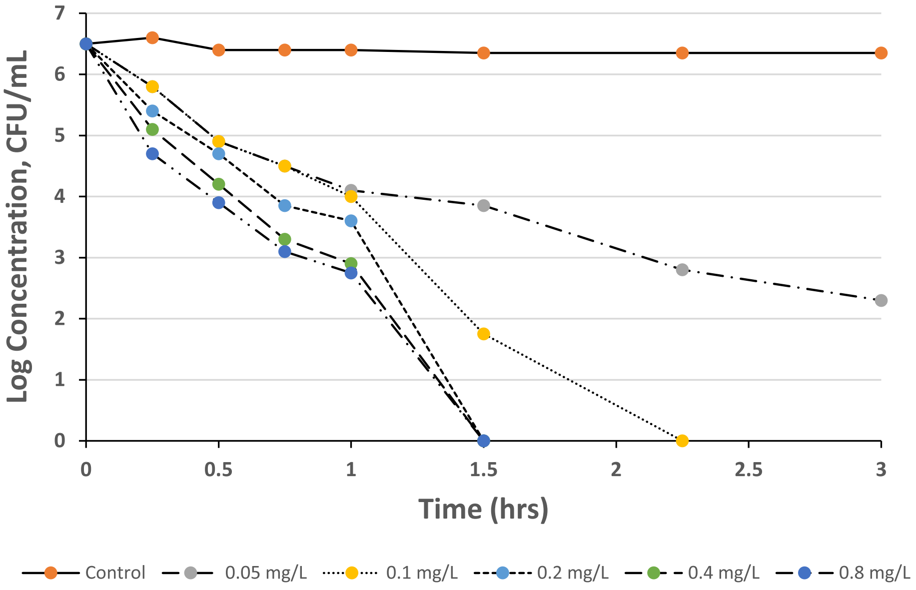


FIGURE 2 Copper inactivation of *L. pneumophila*. Adapted from Lin et al., 1996.

Copper-silver ionization (CSI) can also benefit from additional synergies with residual disinfectants. For example, Yahya et al. (1989) showed that cultures of *Escherichia coli* (*E. coli*) and *Streptococcus faecalis* were individually tested in autoclaved well water dosed with 460 μg/L copper and 75 μg/L silver and with or without 0.20 mg/L free chlorine. Copper-silver ions in combination with free chlorine reduced bacterial numbers more rapidly than chlorine, copper, or silver ions alone. Landeen et al. (1989) showed that inactivation of *L. pneumophila* was significantly greater ($p < .05$) in systems for which copper and silver (400 and 40 μg/L) were added to free chlorine (0.1 to 0.4 mg/L) than with free chlorine alone. Inactivation rates were increased in warmer water (39°C). Straub et al. (1995) also reported copper synergy with chloramine disinfection for *E. coli* and MS2 phage.

Studies have shown the effectiveness of CSI for other bacteria common in building plumbing systems, including *Pseudomonas*, *Stenotrophomonas*, *Acinetobacter*, and *Mycobacterium*. Huang et al. (2008) showed that copper (at 0.2–0.8 mg/L) and silver (at 0.04–0.08 mg/L) ions were effective in achieving more than 5 logs of inactivation of *P. aeruginosa* and *S. maltophilia* within 6 h. However, *A. baumannii* were more resistant and required 96 hrs. to achieve the same level of inactivation. Shih and Lin (2010) reported that both planktonic and biofilm-associated *P. aeruginosa*, *S. maltophilia, and A. baumannii* were inactivated with CSI treatment (Cu/Ag concentrations ranged 0.2/0.02 to 0.8/0.08 mg/L). *M. avium* was shown to be 100-fold less sensitive to copper and silver ions than *Legionella* (Lin, Vidic, et al., 1998b), but the authors concluded that CSI treatment would still be effective to eliminate the microbe in hospital water systems with a modeled concentration multiplied by time (CT) of 82 mg-h/L for a 3-log inactivation. Kusnetsov et al. (2001) reported that *Mycobacterium* spp. were not controlled by CSI treatment, but copper levels averaged 120 μg/L and silver levels were <10 μg/L—which are below recommended levels (Lin et al., 2011). Field studies of CSI (copper/silver ions targeted at 0.2–0.4 and 0.02–0.04 mg/L, respectively) have reported effectiveness in reducing fungi in hospital water systems (Pedro-Botet et al., 2007; Chen et al., 2013). Stüken et al. (2018) reported that CSI treatment altered the microbial composition of biofilms compared to untreated controls.

6 | COPPER-SILVER RESISTANCE

Rusin and Gerba (2001) defined resistance as the ability of a bacterial population to grow in working concentrations of an active disinfectant. Tolerance was defined as the ability of an organism to survive short-term exposure to a disinfectant or to survive for a longer period of time than more-sensitive bacterial strains. Many published papers describing copper-silver resistance would be considered as mere tolerance following these criteria, making a thorough discussion of CSI resistance problematic. *E. coli* and *Salmonella* resistance to silver is controlled by two genes: SilS, an ATP kinase sensor, and SilR, a DNA-binding activator responder (Silver, 2003; Silvestry-Rodriguez et al., 2007). To date, the literature has not demonstrated the presence of genomic silver resistance (i.e., sil operon) in *Legionella* species (June & Dziewulski, 2018; Sütterlin, 2015).

Escherichia coli possesses a periplasmic multicopper oxidase that is encoded by the gene *cueO*. Gene expression increases upon exposure to copper resulting in the oxidization of the more toxic form of copper (Cu+) to the less toxic form (Cu2+) (Grass & Rensing 2001). *E. coli* also possesses the copper efflux protein CopA, which removes Cu+ from the bacterial cell (Rensing et al., 1999). When the CopA protein is inhibited, hypersensitivity to copper exposure in induced. *L. pneumophila* possesses the ATPase LpCopA protein with 45% identical amino acid sequence with the *E. coli* CopA (Bondarczuk & Piotrowska-Seget, 2013; Kim et al., 2009). Although *L. pneumophila* is capable of counteracting copper ROS production with superoxide dismutase and copper efflux resistance mechanisms have been identified, it is important to note that copper resistance genes found in other gram-negative bacteria have not been located in *Legionella* species (June & Dziewulski, 2018). Bédard et al. (2021) isolated a strain of *L. pneumophila* from biofilms in a heat exchanger that was resistant to 5 mg/L of copper, although a similar strain isolated from the water was sensitive to copper. The cause of the resistance was not known but is suspected to be due to the presence of copper plumbing. The resistance to copper was evidenced by an increased expression of the *copA* gene. Stüken and Haverkamp (2020) reported an increase in antibiotic resistance genes in biofilms treated with CSI, although the details of the CSI treatment were not provided.

Although some anecdotal reports of *Legionella* resistance to CSI treatment have been published—particularly when low levels of silver (e.g., 10 μg/L) were used (Rohr et al., 1999)-no studies recovered in this review demonstrated resistance to CSI when the system was properly designed and operated. Therefore, adequate design and operation are critical to the successful outcome of CSI treatment.

7 | DESIGN, OPERATION, AND MAINTENANCE OF CSI SYSTEMS

7.1 | CSI system design

Since the success of treatment for *Legionella* management depends on the efficient delivery of target levels of copper and silver ions, the design, operation, and maintenance of CSI system are of the utmost importance. In its simplest form, CSI systems are based on the electrolytic production of copper and silver ions from a metal electrode, but the details of the engineering and operation of the system are important to the consistent delivery of copper and silver ions into water systems. It is important to note that there is no industry standard for the design of CSI systems, so it's necessary to carefully examine the details of the system components to ensure that they are appropriate to deliver the desired dose.

All US EPA-registered biocides (like copper/silver) must have an U.S. EPA registration number, which consists of a company number and a product number. When choosing a CSI system for *Legionella* control, check for the U.S. EPA registration number to ensure that the product has demonstrated performance. All water contact materials need to meet NSF 61 standards. Finally, it's important that the control unit and water-bearing equipment be ETL (Edison Testing Laboratories) or UL (Underwriters Laboratory) for electrical safety for water treatment appliances and industrial control equipment (or equivalent).

Key components of a CSI system include the electrodes, flow cells, power supply and control panel, flow meter and web interface. Critical characteristics for the components are described below:

- Electrode. The electrode is typically comprised of an alloy of copper and silver which releases these ions by an applied direct current. The composition of the electrodes can vary from 50:50 copper/silver to levels greater than 90:10 copper/silver. The U.S. military specifies the use of 99.99 percent pure copper and silver, with a minimum ratio of 30 percent silver to 70 percent copper (USACE, 2020). The voltage across the electrode causes the copper and silver ions to be released and over time the electrode will be consumed and become smaller as the ions are released. The size of the electrode should be proportionate to the flow rate of water to be treated. The exact specification depends on the conductivity of the water, the volume of water (per min) to be treated, and the power demand of the unit. As a rule of thumb, a larger electrode (e.g., greater surface area) is needed for waters of low conductivity.

  The applied electrical voltage will be influenced by the distance and configuration between the electrodes. As the electrode is consumed, spacers can be inserted to keep the distance between flat electrodes constant (Figure 3), but these changes are more difficult to control for rod-shaped electrodes, which become more rounded and conical as they wear (Figure 3).
  Walraven et al. (2015) examined separate high-purity copper and silver electrodes and electrodes comprised of various blends of copper/silver metals. They found that the release of copper and silver from the separate electrodes followed Faraday's Law and could be accurately dosed, but the alloy electrodes tended to release more copper than silver due to the "noble nature" (more inert) of the metal. However, since targeted copper doses are typically greater than the desired levels

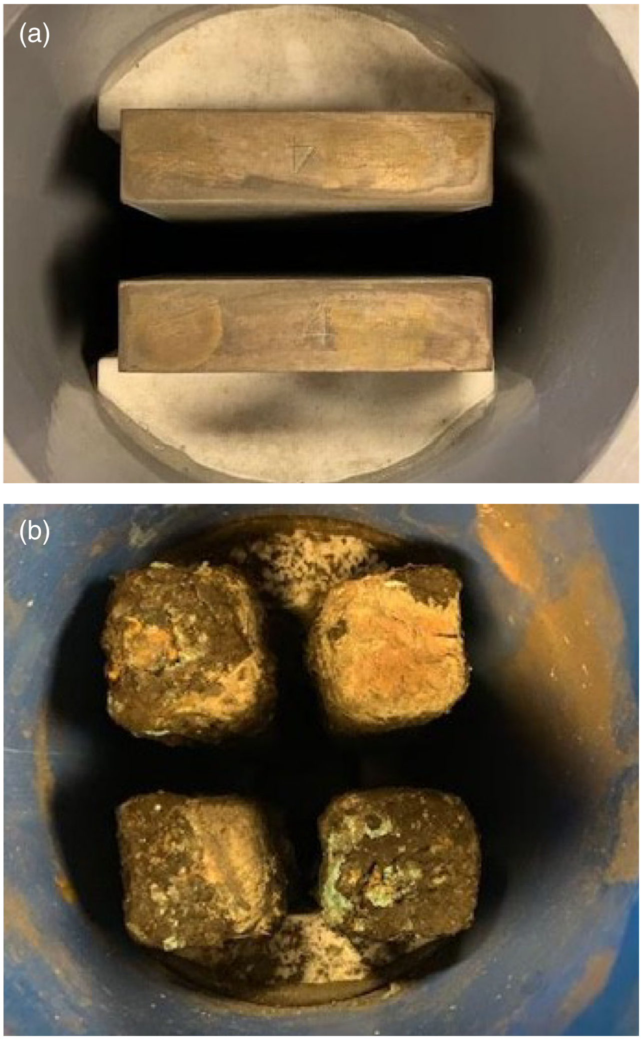


FIGURE 3 Examples of various electrode configurations. The flat plate configuration can maintain a constant distance between the electrodes for more uniform copper/silver generation. Photos provided by LiquiTech with permission.

of silver, this difference in the nobility of the metals can be incorporated into the specific copper/silver composition of the electrode and the applied voltages managed by the CSI controllers. As a result, many combined CSI electrode systems are able to accurately achieve the target levels of copper and silver in the applied waters.

- Flow cells. The flow cells should be constructed of non-conducting materials (e.g., PVC) or coated with a non-conducting layer to prevent the formation of stray currents from the electrode. However, non-conducting (epoxy) coatings can wear over time, exposing the flow cell surface and result in pitting and premature failure (Figure 4).

  The flow cells should be installed in a manner that permits easy access and removal of the electrodes for routine maintenance and cleaning. Inspection and cleaning/descaling of the electrodes should be done on a monthly basis as a scale will naturally form on the electrode surface due to the electrical current and heat generated by the electrode.

  Because the electrical current is applied to the electrode in the flow cell, the entire apparatus should be ETL/UL certified for electrical safety (not just the controller).

FIGURE 4 Example of pitting in a metallic flow cell when the non-conducting layer has eroded. Photo provided by LiquiTech with permission.

- Power supply and control panel. The power supply and control panels are the muscle and brains of the CSI system. It's important that the power system is capable of supplying an adequate amperage (typically in the range of 0.5–10 amps) to the electrodes—determined by the volume of water to be treated. Depending on the flow rate, the controller applies a direct current voltage to the electrode to achieve the desired amperage across the electrodes. In short, amperage means ions. If the unit can only deliver milli-amps, then the CSI system will be limited to only being capable of treating small flow rates. As the system operates, a scale will naturally form on the electrodes. The controller will help delay scale formation by periodically switching polarity across the electrodes allowing the electrodes to wear evenly, and resist scale by remaining cool. The controller should be able to measure the increased resistance caused by the scale and compensate by increasing the voltage. Alarms can be generated for maintenance and cleaning when maximum voltages are being approached. The control panel and the flow cell should both be ETL/UL certified for electrical safety.

- Flow meter. An ultrasonic flow meter must be installed on the water inflow line so that ion dosing is proportionate to the flow rate. For recirculating heating systems, this flow meter would measure the new cold-water makeup to the heating system. For cold water treatment, the flow meter would measure the total inflow to the building. Cold water CSI systems typically treat a side-stream of the flow and blend the concentrated ions in the side-stream into the full flow of the building (Figure 5a). This provides a steady flow through the units which is required for adequate dosing. Additionally, it controls the total flow through the equipment, eliminating wear on the system. It is important, however, to carefully measure and match the side-stream flow to the full building supply. Hot water systems typically have a flow much smaller than the cold-water supply and typically all the flow goes directly through the CSI system (Figure 5b). In all cases, there should be a smooth linear response of ion concentration to each 0.1-gallon change in flow.
- Web interface. Modern CSI systems typically have the options for a web-based interface so that the operations and performance of the system can be remotely monitored by the manufacturer. This remote functionality can include real-time display and alarms, system diagnostics, system configuration, data logging, and the ability to perform all control function adjustments. Because the facility where the CSI system is installed may not have the water treatment expertise to manage the system, remote monitoring and operations are a huge benefit to meeting *Legionella* water quality goals.

7.2 | CSI system operations

The goal of a CSI system is to maintain consistent levels of copper and silver in the plumbing system to achieve the desired level of control for *Legionella* and other waterborne pathogens. As with any process, the key to achieving its goal is the proper operations and maintenance of the system.

Routine monitoring of copper and silver ions is important to validate that the CSI system is delivering the target ion concentrations. Typical ranges for copper ions are 0.2 to 0.8 mg/L and 20 to 80 μg/L for silver ions (Lin et al., 2011), but the concentrations needed for effective microbial control will depend on water chemistry and other operational variables. Liu et al. (1994) observed that CSI treatment decreased positive culture detection of *Legionella* when copper concentrations were greater than 0.4 mg/L and silver concentrations were greater than 40 μg/L. Likewise, Walraven et al. (2016) reported that copper 400 μg/L (range 200-600 μg/L) and silver 40 μg/L (range 20-60 μg/L) was effective in eliminating *Legionella* in five different building systems. To reduce operating costs and maintenance, copper and silver ion levels can be reduced once *Legionella* control is established and validated by routine monitoring.

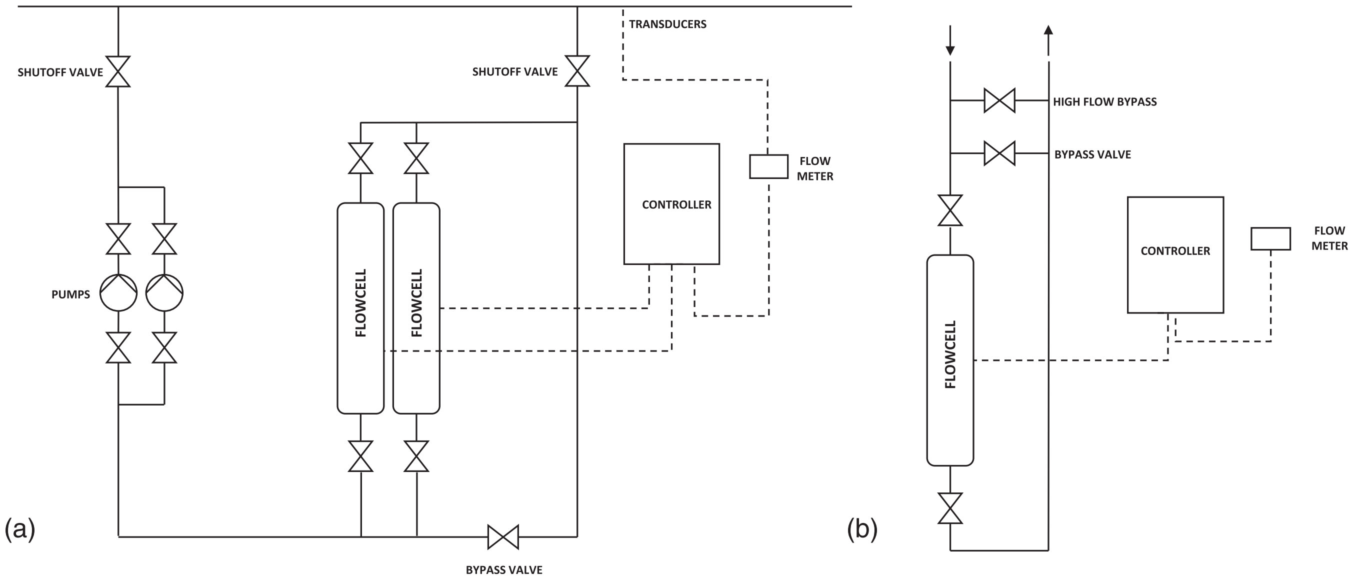


FIGURE 5 Schematics of typical CSI Installations. (a), a side stream unit, (b), a flow through unit.

7.2.1 | System commissioning

Upon commissioning of a new system, monitoring should be conducted more frequently (e.g., weekly) to ensure that target ion levels are being achieved, and then subsequently on a monthly basis to validate routine operations. Testing should be conducted at a variety of distal locations representative of the building piping to ensure proper dispersion of copper/silver throughout the system. The number of monitoring locations will vary depending on the size and complexity of the system. Although no official guidelines were found, experts (T. Schira of Liqui-Tech) recommend testing a minimum of 6 representative locations with an ideal of 20–25% of outlets tested each quarter, to demonstrate the stability of the copper/silver ions within the network. For point-of-entry treatment systems, monitoring should be representative of both the hot and cold-water networks. Once the performance of the CSI is established, the number of monitoring locations or the frequency of testing could be reduced. Although there are colorimetric kits for the measurement of copper, monitoring of copper and silver concentrations should be done by atomic absorption spectroscopy or inductively coupled plasma mass spectrometry (ICP-MS) (U.S. EPA method 200.8). Testing for *Legionella* should be done at least quarterly (and perhaps more frequently during commissioning) to verify that the CSI system is achieving adequate results.

7.2.2 | Analytical methods and monitoring

Samples collected from CSI-treated waters should be neutralized prior to culturing to stop the biocidal action of copper and silver—particularly when the samples are shipped to a laboratory for analysis. Lai et al. (2021) compared two neutralizing agents (50 mg/L ethylenediaminetetraacetic acid disodium salt dihydrate [Na2EDTA·2H_2O] or 180 mg/L sodium thiosulphate pentahydrate [$Na_2S_2O_3 \cdot 5H_2O$]) for their ability to deactivate concentrations of 0.08 mg/L of silver and 0.6 mg/L of copper ions for *L. pneumophila* and *P. aeruginosa* spiked in bottled (Evian) water. Analyses performed by two independent labs showed that 180 mg/L $Na_2S_2O_3 \cdot 5H_2O$ completely neutralized the biocidal actively while 50 mg/L Na2EDTA·2H_2O permitted continued inactivation of the organisms such that the organisms were not detected by culture after 24 and 48 h. Although some official guidelines recommend the use of EDTA for neutralization of metal ions, the authors noted that sodium thiosulphate should be the preferred agent for neutralization of CSI-treated samples.

Monitoring of CSI efficacy (and all other treatment processes) is most commonly done by culturing *Legionella* isolates, and a variety of culture techniques are available (Vittal et al., 2022; Walker & McDermott, 2021; Wroblewski et al., 2022). It is possible that all disinfection processes can result in a "viable but not culturable" or VBNC condition where cells can retain metabolic functions (.e.g., enzyme activity or DNA replication) but not produce visible colonies on standard culture media. When exposed to copper ions alone, the culturable counts of *L. pneumophila* were decreased, but not the number quantified by DNA-based methods (Buse et al., 2017; Gião et al., 2015; Proctor et al., 2017). Hwang et al. (2006) reported that *L. pneumophila* entered the VBNC when suspended in synthetic drinking water but was completely inactivated within 8 h when exposed to CSI (1.0 mg/L copper, 0.1 mg/L silver). *L. pneumophila* intracellular in *Acanthamoeba polyphaga* cells were inactivated by 7 logs by the CSI treatment over a 7-day period. The public health significance of VBNC cells of *L. pneumophila* is unclear, as Dietersdorfer et al. (2018) reported that VNBC cells of *L. pneumophila* infected human macrophages at rates of 100 to 400 times less than culturable cells. No outbreaks attributed to VBNC cells have been reported.

7.3 | CSI system maintenance

The accumulation of sediment within a plumbing system will protect microorganisms from all disinfectants. Routine weekly flushing, particularly of slow moving or stagnant areas is important to both remove sediment and introduce fresh levels of copper and silver ions (Liu et al., 1994). Sediment can originate from the source water and materials in the public water supply but also result from iron, zinc, aluminum, and manganese from an internal corrosion of metallic pipes and appurtenances within the plumbing systems. Recirculating systems can accumulate 3–20 times more sediments arising from the corrosion of metallic pipe material and the anode rods (Cullom et al., 2020). Sediment can accumulate in tanks and slow-moving parts of the plumbing system and accumulate nutrients that promote microbial growth and provide protection from disinfection. The duration of flushing will depend on the specific system but should be sufficient to expel all stagnant water. Monitoring of water temperatures during flushing can help verify that the temperature of the distal site flushed water is at the same as the core water within the system.

Regular cleaning of the electrodes should be done to remove the accumulated scale which will form normally from calcium carbonate and other minerals in the water (Lin et al., 1998a). Scale removal is typically achieved using a mild acid (e.g., muriatic acid), however, due to safety concerns the electrodes are normally shipped to the vendor rather than treated on-site. As the electrodes wear, the metal loss will require recalibration of the voltage and respacing of the electrodes. With plate electrodes, spacers can be inserted to maintain a fixed separation between the electrodes (Figure 6). With bar electrodes, such reconfigurations are more difficult.

Water management plans should anticipate events where there is a disruption in potable water service to the building due to planned or unplanned events (e.g., main repair, breaks, loss of pressure, etc.) or construction or renovation of the building plumbing. The prolonged disinfection capacity of CSI treatment is able to provide adequate microbial control even for short durations of interruption (Lin et al., 2011). However, during periods of water disruption, sediment and turbidity from distribution system mains can be washed into building plumbing networks and impair CSI treatment. Kessler et al. (2021) reported an outbreak of *L. pneumophila* in a hospital system following disruptions of the drinking water supply in a hospital system, despite the presence of a CSI system (unfortunately the details of the CSI operation were not provided). Water management plans should be developed to either switch to alternative sources of potable water or flush the pipe network to remove the sediment and include procedures of testing to determine any risks associated with a water interruption. Whole-building filters can remove this debris and are being installed in buildings with frequent interruptions (Figure 7). The stainless steel filters do not affect disinfectant residuals.

8 | REGULATORY ISSUES

8.1 | Secondary maximum contaminant levels

Copper is an essential trace mineral necessary for human survival and plays a role in the formation of red blood cells and in maintaining nerve cells and the immune system. However, some individuals with altered copper metabolism, called Wilson's disease, suffer from excessive copper stored in various body tissues, particularly the liver, brain, and corneas of the eyes (Lung et al., 2015). As a result, the U.S. EPA has set a non-enforceable secondary maximum contaminant level (SMCL) of 1.0 mg/L for copper (USEPA, 2022). This secondary standard is based on aesthetic impacts due to taste, color, or staining. In addition, the U.S. EPA Lead and Copper Rule (USEPA, 2021) require drinking water utilities to monitor water at customer taps and implement corrosion control if greater than 10% of the samples exceed 1.3 mg/L Cu. Dietrich and Burlingame (2015) noted that while the SMCL of 1 mg Cu/L is less than the Lead and Copper Rule's Action Level (AL) of 1.3 mg Cu/L and thus consistent with protecting human health, the level is higher than the human flavor threshold for copper (0.4–0.8 mg soluble Cu/L in distilled water or tap water).

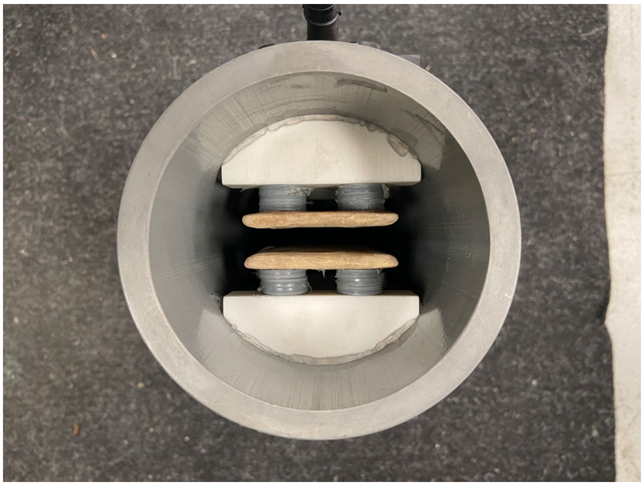


FIGURE 6 Example of inserted spacer to maintain fixed separation distances between the worn electrodes. Photo provided by LiquiTech with permission.

According to the World Health Organization (WHO 2011) only a small percentage of ingested silver is absorbed., with retention rates in humans and laboratory animals ranging between 0% and 10%. Argyria, an irreversible but non-dangerous skin discoloration, occurs when high levels (e.g., grams) of silver are ingested. An oral No Observable Adverse Effect Level (NOAEL) for argyria in humans for a total lifetime intake of 10 g of silver was estimated on the basis of epidemiological and pharmacokinetic data (WHO 2011). The US EPA (2022) recommends an SMCL for silver of 0.1 mg/L. The WHO has stated that this amount of silver for the treatment of water could easily be tolerated since the total absorbed dose would only be half of the NOAEL after 70 years (WHO, 2011). Silvestry-Rodriguez et al. (2007) notes that more than 50 million people in the United States drink water from point-of-use filters that are impregnated with silver and that leach silver at low levels (1–50 ppb) with no known observable adverse health effects. Therefore, the CSI systems operating within the normal target ranges of 0.2 to 0.8 mg/L for copper ions and 20 to 80 μg/L for silver ions would be well below the SMCL standards set by the U.S. EPA and the WHO.

8.2 | State approval of CSI installations

Under the SDWA (40 CFR §141.2) a building water system that treats its drinking water could be considered a consecutive system (e.g., a water system that receives some or all of its finished water from one or more wholesale suppliers). However, 40 CFR §141.29 provides “flexibility” to state agencies to modify the monitoring requirements to the extent that the interconnection

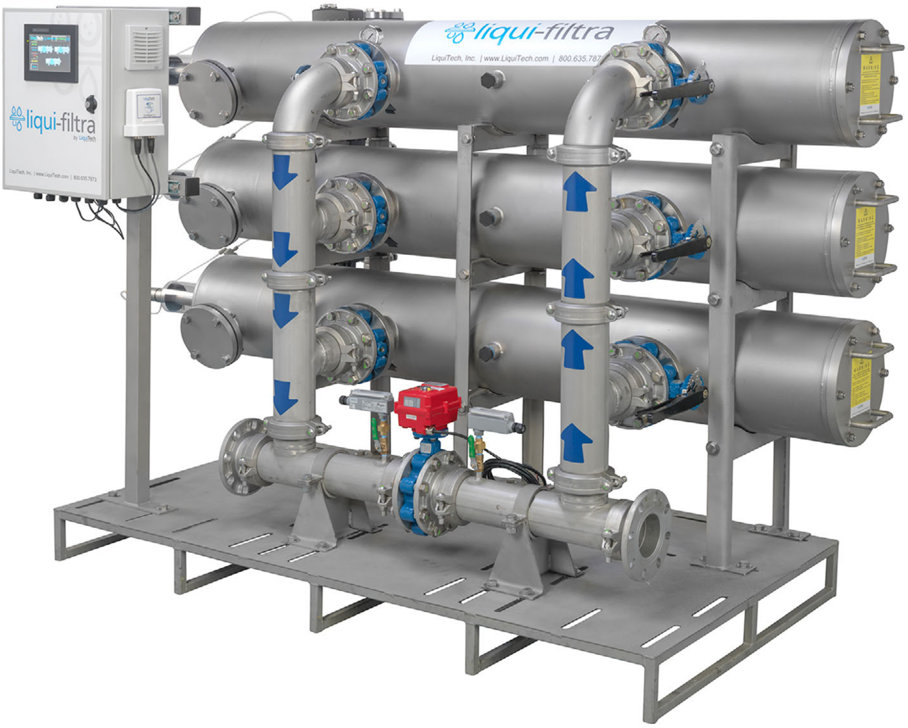


FIGURE 7 Example of a whole-building point of entry filtration system. Photo provided by LiquiTech with permission.

between the building water system and the water utility justifies treating them as a single system. The language of 40 CFR §141.29 is as follows:

> When a public water system supplies water to one or more other public water systems, the State may modify the monitoring requirements imposed by this part to the extent that the interconnection of the systems justifies treating them as a single system for monitoring purposes. Any modified monitoring shall be conducted pursuant to a schedule specified by the State and concurred in by the Administrator of the U.S. Environmental Protection Agency.

Therefore, States have the flexibility, if they choose, to consider buildings that implement CSI treatment (and other treatment processes) as part of the larger water utility. Currently, many states would not regulate CSI treatment of hot water systems (ASDWA, 2019) as hot water is not typically recommended for ingestion nor are hot water samples required in any drinking water regulation. Where cold water point of entry CSI treatment is practiced, the only regulatory requirements should be for routine monitoring of copper and silver provided that the potable water supply is already in compliance with all other drinking water requirements. It is an unnecessary cost and a disincentive to building owners for regulators to apply other drinking water requirements (e.g., total coliform or disinfectant by-product monitoring) that have no relationship to the added CSI treatment. However, because there is no uniformity in state oversight of building water treatment, it is important for the building owner to confer with state officials on the specific requirements for their installations.

9 | IMPACT OF WATER QUALITY PARAMETERS ON CSI TREATMENT

A number of water chemistry, physiochemical, and environmental factors can influence the performance of CSI treatment. It is important for the successful implementation of CSI treatment to consider the impact of these variables during planning, commissioning, and system operations.

9.1 | Conductivity

The conductivity of water is influenced by the concentration of dissolved salts and other inorganic chemicals and affects the ability of water to pass an electrical current (Dziewulski et al., 2015; June & Dziewulski, 2018). Conductivity is measured in micromhos per centimeter (μmhos/cm) or micro-Siemens per centimeter (μS/cm). Conductivity is also affected by temperature: the warmer the water, the higher the conductivity. Water with low conductivity will require a greater voltage to a given electrode to achieve the desired amperage across the electrodes. CSI systems with a weak power supply, incorrect flow cell design, geometry or maintenance may perform poorly in low-conductivity waters. Similarly, the conductivity of a potable water supply can change seasonally or when sources of water vary between a groundwater and a surface water supply. In some potable water supplies with both surface and groundwater sources, the conductivity at the interface of the surface and ground water supply in the distribution system can change daily or even hourly depending on the water demand. In these cases, the controller will need to sense and adjust the power to the electrodes to maintain the desired ion concentration as the conductivity changes.

9.2 | Temperature

Copper and silver ions are more biocidal, and have a greater impact on microbial cells, at higher temperatures (Landeen et al., 1989). Sicairos-Ruelas et al. (2019) reported that a reduction in temperature (from 24 to 4°C) had a much greater impact on silver ions alone (100 μg/L) than the combination of silver/copper (100/400 μg/L). Cloutman-Green et al. (2019) reported effective *Legionella* management in a healthcare building hot-water system operated at 42°C (range 37°C to 44°C) supplemented with CSI operated at 0.37/0.034 mg/L, respectively. The authors reported a reduction in energy and carbon emissions of 33% and 24%, respectively, compared to an equivalent temperature-controlled system. Blanc et al. (2005) however did not have good results with CSI in their hot water system at 50°C, but then their copper/silver electrodes composed of 92/8% copper:silver and silver ion levels were maintained below 10 μg/L. The authors speculated that the low silver levels might have hampered the performance of their system.

Because super-heated water cannot be safely delivered to building occupants without mixing with a cold water supply to avoid the risk of scalding, it is critical to consider in hot water CSI treatment the potential for dilution of the copper/silver ions when the water is mixed with untreated cold water in thermostatic mixing valves to achieve water temperatures less than 120°F (49°C) (Figure 8). The bottom panel of Figure 8 shows that once the super-heated water is cooled, it enters the

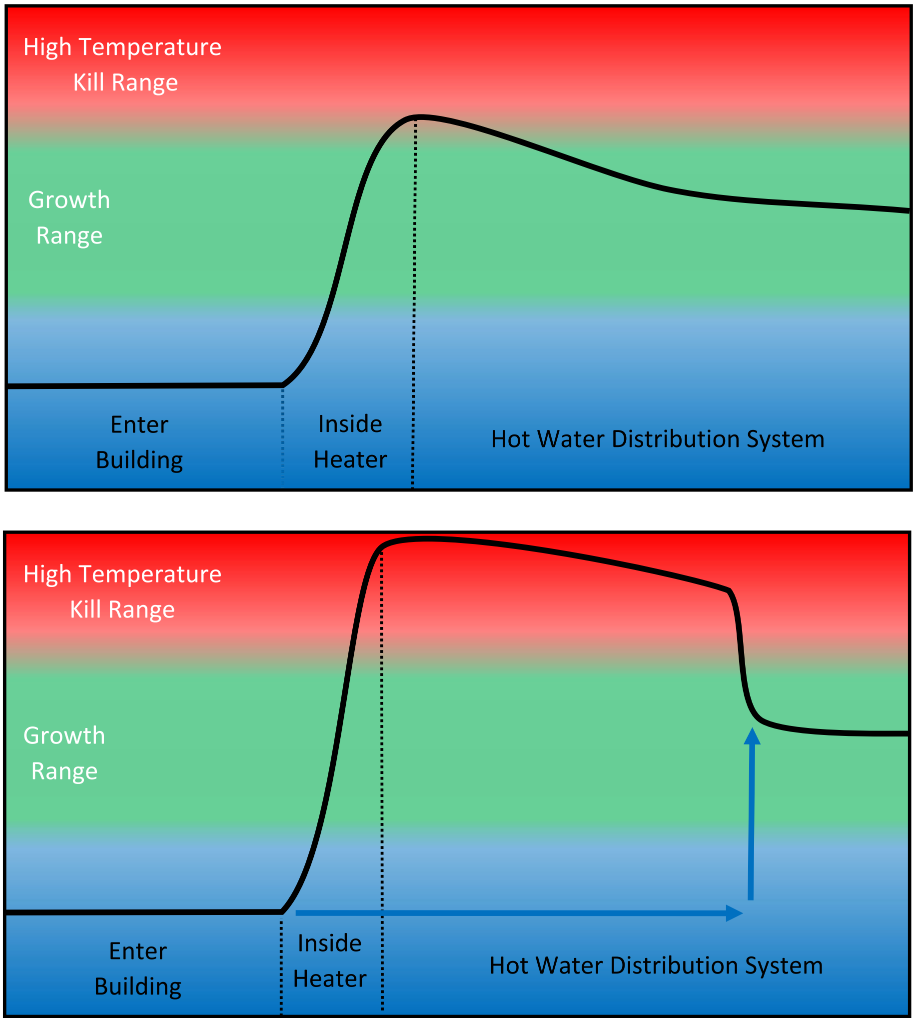


FIGURE 8 Heat profiles for hot water systems. In the top figure, water is heated to 120°F (49°C) and distributed throughout the building with no dilution of copper/silver ions. In the bottom figure, water is heated and distributed at 140°F (60°C), but cooled to 120°F (49°C) at a thermostatic mixing valve. The incoming cold water both dilutes the copper-silver ions and provides a favorable growth condition for *L. pneumophila*.

temperature range favorable for *Legionella* growth. However, the top panel shows that CSI-treated water that is heated and distributed at 120°F (49°C) can deliver the biocidal ions completely to the distal outlet. In the Cloutman-Green et al. (2019) example, distributing the hot water at 42°C avoided any dilution in the effectiveness of the CSI treatment. Moreover, heating the hot water to >60°C can reduce the solubility of ions and oxygen, which are important for the efficacy of CSI treatment. Stout et al. (1998) reported better control of *Legionella* in hospital water systems using CSI (mean copper/silver ion concentration of 0.29 and 0.054 mg/L, respectively, in the hot water tanks and 0.17 and 0.04 mg/L from distal outlets) than super heat (60–77°C) treatments (e.g., outlets flushed for 20–30 min).

9.3 | Oxygen

As described above, both copper and silver act on microbial cells through, in part, the formation of reactive oxygen species. Therefore, oxygen is an important component for CSI treatment. Under oxygen-depleted conditions, copper ions are still capable of *Legionella* inactivation but at a slower rate and to a lesser extent (Cross et al., 2003; Grass et al., 2011). Therefore, regular flushing of building plumbing is needed to avoid stagnant water conditions that could lead to anoxic conditions.

9.4 | Flow

Balancing the flow through the CSI system is important in achieving the proper concentration of copper/silver ions in the water. Too low of a flow can lead to stagnation and lack of release of copper, silver, and reduced oxygen levels, as noted above. However, too high of flows can erode the copper/silver electrodes, and strip the metal from the surface. Triantafyllidou et al. (2016) reported aesthetic problems (e.g., staining) and variable copper and silver levels in a CSI hospital system where incorrectly balanced flow valves resulted in variable operations. Moreover, the installation of a water softening unit after the CSI treatment in the hospital studied by Triantafyllidou et al. (2016) resulted in the loss of 10–90% of copper and silver levels (an average of 51–72%), further adding to an variable performance of the system.

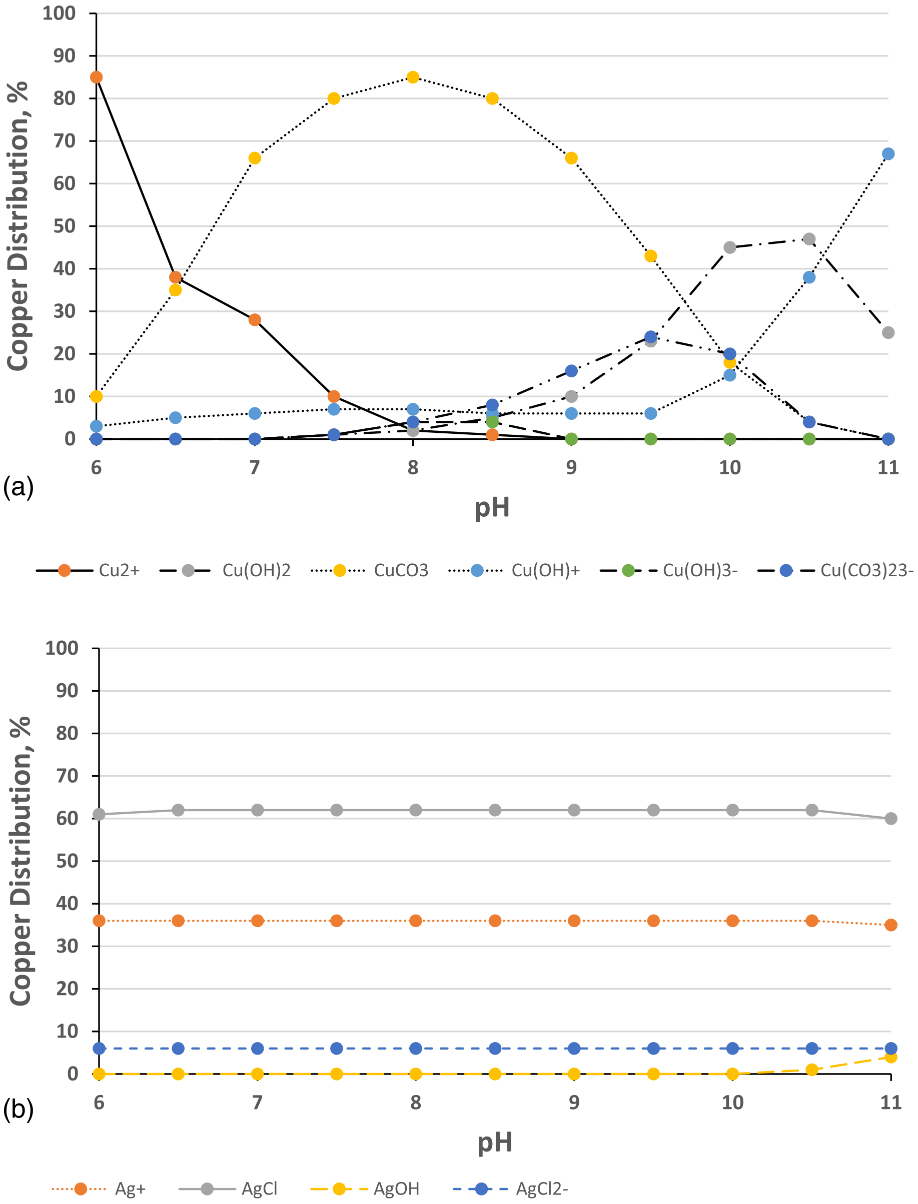
9.5 | pH

Alkaline conditions affect the solubility and biocidal properties of copper to a much greater extent than silver. Lin et al. (2002) reported that higher pH values (>8.0) led to a shift in the predominant copper species from positively to negatively charged ions—which impacted the association of copper with bacterial cells (Figure 9). A copper ion concentration of 0.4 mg/L did not eradicate *Legionella* at pH 9 (Lin et al., 2002) and the solubility of the copper complexes decreased as the pH increased. Similarly, Song et al. (2021) reported reduced biocidal activity of copper ions when pH values changed from 7.0 to 8.5, but *L. pneumophila* levels were still reduced by 1.34 logs in 360 min. Silver, on the other hand, was not affected by changes in pH; silver at 0.08 mg/L was able to achieve a millionfold reduction in the culturability of *Legionella* in 24 h at all pH levels tested (pH 7–9) (Lin et al., 2002). Although the poor performance of CSI treatment at high pH levels has been reported (CDC, 1997; Lin et al., 2002), the biocidal capacity of silver ions at elevated pHs suggests that *Legionella* control is still achievable. Dziewulski et al. (2015) reported good *Legionella* control in several hospital facilities using CSI at elevated pH levels (pH 8.6–9.7). At the high pH levels, 80% of copper ions precipitated to levels averaging 0.035 mg/L, but the concentration of silver (median 0.03 mg/L) was sufficient to control *L. pneumophila* s.g. 1, *L. pneumophila* s.g. 6, and *L. anisa* under the treatment conditions employed. The trace level of free chlorine (averages of 0.12 to 0.17) may also have provided synergistic treatment along with the silver. The point is, that although a decline in copper availability occurs at high pH levels, control of *Legionella* is still possible with proper silver dosing, monitoring, and system management. Lin et al. (2002) reported that a Wisconsin hospital using CSI treatment, reduced the pH of their incoming water through the addition of food-grade sulfuric acid from pH 8.5–8.8 to 7.0–8.0 and eliminated culturable *Legionella* after the intervention.

9.6 | Chloride, alkalinity, hardness, phosphate, dissolved organic carbon

Figure 9 shows that chloride anions can be complex with silver ions in water. At low concentrations of chloride (also bromide and iodide), silver maintains the ability to bind to bacteria and exert biocidal effects; at moderate levels of chloride, silver is precipitated (e.g., silver chloride [AgCl]); at high concentrations of chloride, the silver compounds become bioavailable again as anions (e.g., $AgCl2^-$) (Silver, 2003). Lin et al. (2002) reported that increasing the chloride ion concentration from 15 to 50 mg/L reduced the availability of positively charged silver ions from 56 to 26% of the total silver concentration. According to a USGS report (Mullaney et al., 2009), the

FIGURE 9 Impact of pH and chloride ions on copper and silver ion speciation in a chemical-equilibrium model. Higher pH favors copper anions in solution (top), while it has relatively little impact on silver ion distribution (bottom). Adapted from Lin et al. (2002).



median concentration of chloride in drinking-water supply wells was 26 mg/L, but can range as high as the SMCL of 250 mg/L. Seasonal variations in chloride levels can be influenced by run-off from road salts.

Lin et al., (2002) also reported that changes in alkalinity (50, 100, and 150 mg/L $NaHCO_3$ at pH 7.0) and hardness (Ca^{2+} at 50 and 100 mg/L; Mg^{2+} at 40 and 80 mg/L) and dissolved organic carbon (0.5 and 2 mg/L humic acid) had no significant impact on the rates of *L. pneumophila* inactivation by CSI treatment. Dissolved organic carbon at 20 mg/L, however, prevented a copper concentration of 0.4 mg/L from killing *L. pneumophila* within 24 h. Sicairos-Ruelas et al. (2019) reported that the inactivation of *E. coli* by 100 μg/L of silver was not affected by the presence of either 3 or 10 mg/L of total organic carbon (humic acid).

A similar precipitation effect on aqueous cuprous and cupric species will occur with anions such as sulfate and phosphate, thereby limiting the amount of available copper for disinfection. Song et al. (2021) reported that the addition of 5 mg/L of natural organic matter (humic and fulvic acids) eliminated the copper toxicity from the water they studied. The addition of orthophosphate (0.5 and 3 mg/L) reduced the biocidal impact of copper by nearly 4-fold. Landeen et al. (1989) cite research showing that phosphate will complex copper ions and reduce the antimicrobial effects of copper and prolong the inactivation times for silver. Orthophosphate is commonly added to potable water supplies to control the corrosion of lead and iron pipes. Typical doses range from 0.2–1.25 mg/L as phosphate but can be as high as 3–5 mg/L during the initial passivation of the potable water system (Schneider et al., 2007).

This discussion demonstrates that it is important to consider the impact of water chemistry (in particular chloride, phosphate, and natural organic carbon) as there may be circumstances where the concentration of these analytes could impact the efficacy of CSI treatment. It is important to conduct a chemical analysis of the water to be treated by CSI and also consider seasonal variations in the values. Use of chemical equilibrium software like MINTEQ, ChemEQL, or MINEQL+ can aid in these evaluations. The potential for interference by these compounds on CSI treatment can be managed by adjusting the copper/silver dosage and/or pretreatment of the water through an ion exchange resin.

9.7 | Biofilm and sediment

Biofilm is defined as the accumulation of microorganisms and extracellular material on a surface and is an important mechanism for microbial survival and growth in water system pipelines. All wetted surfaces have biofilms to a greater or lesser extent. *Legionella* grow within free living amoebae that feed on biofilm bacteria (NASEM 2019). Shih and Lin (2010) developed biofilms of *Pseudomonas aeruginosa*, *Stenotrophomonas maltophilia*, and *Acinetobacter baumannii* in a model plumbing system and treated the network with concentrations of copper/silver targeted at 0.8/0.08, 0.4/0.04, and 0.2/0.02 mg/L. The researchers were able to achieve more than 99.99% reduction of biofilm-associated *P. aeruginosa* within 24 h, more than 99.9% reduction of biofilm-associated *S. maltophilia* within 48 h, and more than 99.9% reduction of biofilm-associated *A. baumannii* within 12 h. Unger and Lück (2012) grew *L. pneumophila* in biofilms on membrane inserts in stagnant water from a large building and found that the biofilm-grown cells were 30–60 times more resistant to inactivation by a solution of silver nitrate (64 μg/L $AgNO_3$; 63.5% atomic silver); likely because the *Legionella*e were intracellular in amoebae. The study did not evaluate the synergy of CSI, as biofilm inactivation is more influenced by the flux of copper and silver ions (i.e., the concentration in the water multiplied by the flow). Since biofilms are fixed on a pipe surface, the flux of a CSI system can deliver grams of copper and silver ions for every megaliter of water that flows through the system.

The accumulation of sediment and debris on pipeline surfaces and in storage tanks and reservoirs creates a habitat for microbes by accumulating nutrients on the surface and protecting the microbes from disinfection. The accumulation of sediment will not only affect CSI treatment but oxidizing disinfectant as well. In one study, Liu et al. (1994) found that distal taps with low use required regular flushing (every other day for 2 weeks) to expose the biofilms to the copper and silver ions and to remove accumulated deposits and scale that would diminish CSI efficacy.

9.8 | Plumbing infrastructure and configuration

The composition and configuration of a building's plumbing can influence the design and operations of CSI treatment. For new plumbing systems, it is recommended to consider background copper levels relative to the CSI treatment output. The objective would be to achieve the desired ion levels (typically copper ions at 0.2 to 0.8 mg/L and 20 to 80 μg/L for silver ions) without exceeding secondary standards. Once *Legionella* levels are controlled, ion levels may be decreased while still achieving effective bacteriological control. Plumbing materials such as iron, steel, brass, or galvanized pipe and/or fixtures can corrode and promote bacterial growth. *Legionella* can colonize a variety of plumbing materials including rubber hoses and gaskets, polyvinylchloride (PVC) pipes, stainless steel, and wood (Lin, Stout, et al., 1998a).

Dead legs or zones of low flow, hot water storage tanks, and low water use can create conditions conducive to *Legionella* growth (States et al., 1998). The flow of copper and silver ions into these areas can be limited by the poor circulation. Lin et al. (1998a) report that the configuration of the hot water tank can play a crucial role in bacterial colonization. Vertical tanks are more likely to be colonized by *Legionella* than horizontal storage tanks, and older tanks are more likely to be colonized than newer storage tanks. Scale and sediment accumulation are positively associated with *L. pneumophila* presence in hot water tanks (Vickers et al., 1987). As mentioned previously, weekly flushing of low-flow lines and tanks is recommended to eliminate the accumulation of sediment.

9.9 | Corrosion

CSI treatment is not reported to cause corrosion of plumbing systems but requires additional controlled research. Chapman et al. (2017) compared galvanized steel corrosion coupons before and after CSI treatment under controlled conditions. The researchers reported no difference in corrosion rates over the 127-day study. Silver covered about 20% of the coupon surface which was expected due to the replacement of the zinc ions with the nobler silver ions. Likewise, Stout & Yu, (2003) reported no problems with the corrosion of piping or plumbing fixtures in the 16 hospitals they studied. Loret et al. (2006) used a series of pipe loops (which also included some dead-end pipes) to test different disinfection techniques and also investigated the corrosion risk of each technique. They reported no increased corrosion for the CSI loop but observed copper deposits on corrosion coupons. Unfortunately, the system used by Loret et al. (2006) had a lot of variation in the CSI operation, making conclusions from this study difficult. Triantafyllidou et al. (2016) observed silver deposited on copper pipe surfaces during the malfunctioning of a CSI treatment system. They theorized that such deposits could stimulate corrosion of the copper pipes due to the electromotive force differences between the metals. The researchers, however, did not detect deposition corrosion of copper pipes in the hospital studied and suggested that further research should be conducted on systems with years of experience in CSI treatment.

9.10 | Disinfectant residuals, byproducts

It has already been noted that chlorine disinfectants (both free chlorine and monochloramine) can create synergies with CSI treatment resulting in increased levels of microbial inactivation (Landeen et al., 1989; Straub et al., 1995; Yahya et al., 1989). The impact of these synergies on the formation of disinfectant by-products is less clear under normal operational conditions. At copper concentrations of 1 mg/L, Blatchley et al. (2003) reported that the increased formation of chloroform was influenced by the type of organic precursor material, pH, and chlorine concentration. Free chlorine residuals in this study ranged from 5–20 mg/L (which exceed the U.S. EPA maximum disinfectant residual levels for drinking water). Other researchers have reported copper catalysis of trihalomethanes, haloacetic acids, haloacetamides, haloacetonitriles, N-nitrosodimethylamine, and total organic halogen (TOX) depending on a variety of conditions (Fu et al., 2009; Hu et al., 2016; Huang et al., 2019; Liu & Croué, 2015; Zhang & Andrews, 2013). In some cases, conditions that favored the formation of certain disinfection byproducts promoted the decay of other compounds. However, to our knowledge, the formation of these byproducts in potable water CSI treatment has not been shown. Allen et al. (2021) reported disinfectant byproduct concentrations decreased by as much as 80% and cytotoxicity decreased by as much as 70% in swimming pool water when a lower chlorine residual (1.0 mg/L) and CSI were used. Further research is needed to examine the formation of disinfectant byproducts in hot and cold-water plumbing systems under normal CSI operations.

10 | CASE STUDIES OF CSI TREATMENT

Stout & Yu, (2003) reported that CSI systems were operational in more than 100 hospitals in the United States, and one-third of the hospitals participating in the Nosocomial Infections Surveillance System surveyed in 1998 used CSI for *Legionella* disinfection. In the intervening 20-year period, installation of CSI equipment has continued, and today it is estimated that over 1000 facilities use CSI treatment (Tory Schira, personal correspondence, 2022), including many of the major cancer and organ transplant centers. The U.S. military (USACE 2020) has specifications for the installation of CSI in health care facilities. The section below provides a number of case studies of successful and unsuccessful CSI installations and discusses the factors influencing the outcome.

10.1 | Acute versus long-term remediation

Often CSI treatment is installed as a proactive strategy for long-term *Legionella* control in health care facilities as part of an overall water management plan. There are numerous reports of the success of CSI treatment for *Legionella* control that span multiple years (Dziewulski et al., 2015; Stout & Yu, 2003). Stout and Yu (2003) collected data from 16 hospitals that used CSI treatment for 5–11 years. After the installation, 50% of the hospitals reported no detection of *Legionella* spp. and 43% had no detections after an additional 5 years. In all the systems there were no cases of hospital-acquired Legionnaires' Disease. Similarly, Dziewulski et al. (2015) reported control of legionellae in two hospital systems with mean *Legionella* colony forming units (CFU) of <10 CFU/100 ml, and <30% positive culture rate for each sampling period (one metric for elevated Legionnaires' Disease risk in a health care facility), along with no cases of legionellosis over the year-long study. Barbosa and Thompson (2016) reported effective control of *Legionella* spp. in a 15-month period, with no detections of the bacteria in 140 outlets in a UK hospital. A review of 10 published studies concluded that CSI is an effective method to control *Legionella*, as long as ion levels are monitored and maintained at effective levels (Cachafeiro et al., 2007).

The monitoring programs for most CSI installations collect *Legionella* samples either weekly at the onset or monthly or quarterly after the water system has stabilized. So, it's not surprising that there are few data on the short-term performance of CSI treatment. Results presented in Figures 1 and 2 show that copper and silver can inactivate *L. pneumophila* within hours and Lin et al. (1996) showed that combined CSI achieved a 6-log reduction of *L. pneumophila* within 1.6 h. But these laboratory results may not reflect the performance of full-scale systems. Figure 10 shows data for *Legionella* results before and after the installation of CSI treatment in an assisted living home in Arizona. The 200-bed facility had incoming municipal water that was consistently above 80°F (26.7°C) and the hot water ranged between 113.7 to 116.2°F (45.4–46.8°C), creating optimal conditions for *Legionella* growth. Prior to the installation of the CSI treatment at the point of entry and the hot water supply on 8/27/20, 90% of the 13 tap samples analyzed were positive for *Legionella* with a combination of *L. pneumophila* sg 2–15 and other *Legionella* species. All of the hot water samples and 4 of 5 cold water samples were positive. Within 5 days of the CSI installation (9/3/20), 80% of the samples were non-detect (ND) for *Legionella* and averaged bacterial concentrations dropped by 2.7 logs (Figure 10). The two positive (hot water) sites were found to have significant flow restrictions and after corrective action was taken to improve the flow, the *Legionella* were eliminated. No other corrective actions were taken. Copper ion levels ranged between 0.41–0.63 mg/L and silver ranged between 0.038–0.075 mg/L in the water samples after 5 days. Sampling of the system approximately 3 months later (1/11/21) showed that all of the sample locations were free of *Legionella* bacteria (Figure 10).

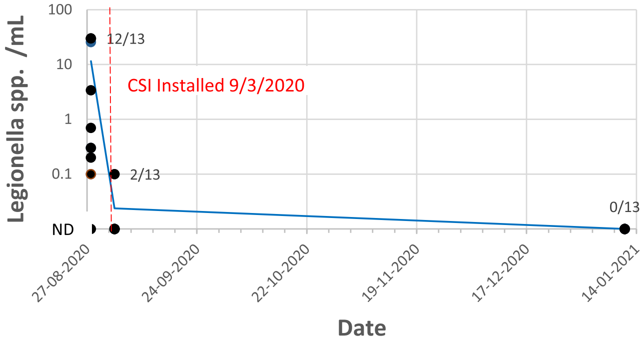


FIGURE 10 Legionella spp. before and after installation of CSI treatment in Arizona. Data labels represent the number of samples positive divided by the total number of samples analyzed. The water had a conductivity of 1100 μS and a pH of 7.5–8.4.

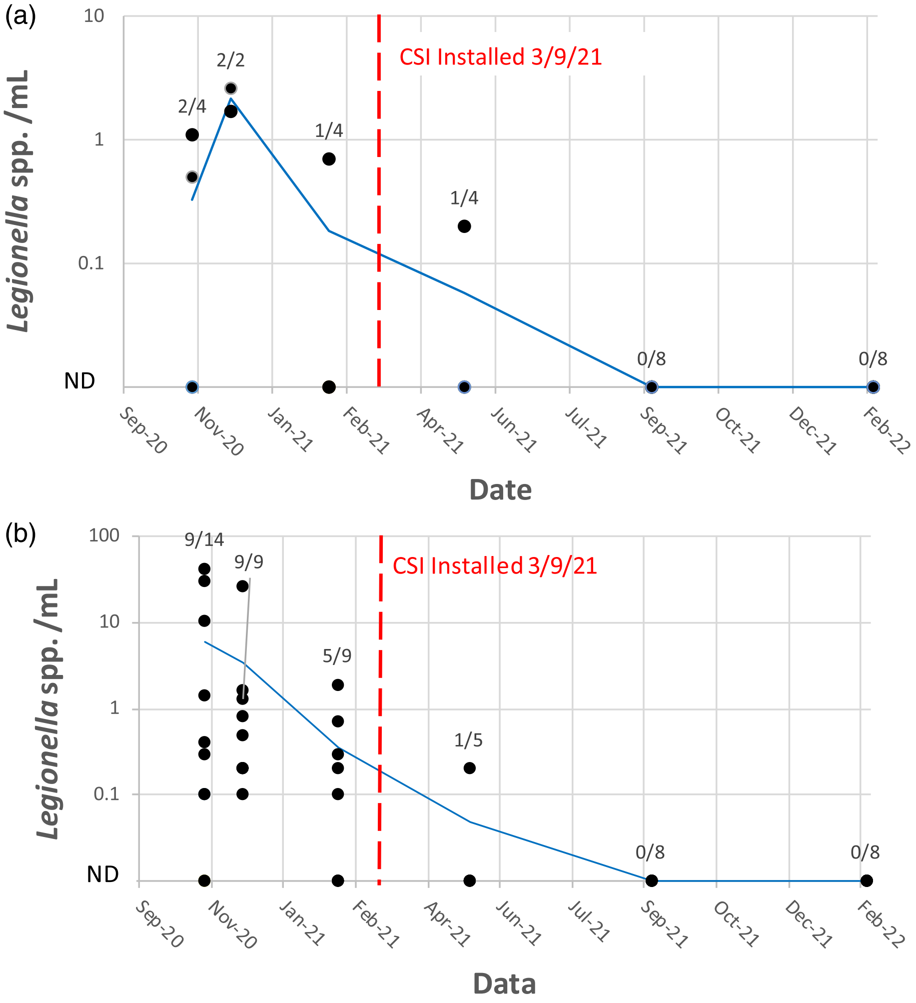


FIGURE 11 CSI treatment in two hospital buildings (A and B). Data labels represent the number of samples positive divided by the total number of samples analyzed.

10.2 | Hospital facility case study

The hospital case study shown in Figure 11 used CSI treatment to control microbially influenced corrosion for many years in the main buildings on its campus, but two buildings were not initially included in the treatment scheme. The California campus has multiple buildings having general medical and surgical centers with 193 beds. Routine monitoring as part of its water management plan detected frequent and elevated levels of non-pneumophila *Legionella* species in November 2020 (Figure 11) despite a free chlorine residual of 2.0 mg/L entering the building. Water management activities (e.g., flushing and testing) in December and January did reduce *Legionella* levels somewhat, but the bacteria were still detected in 55% of the samples in Building A, and 25% of the samples in Building B, with some measurements still exceeding 1 cfu/ml (Figure 11a). Thirty days after CSI implementation, both the frequency of detection and *Legionella* concentrations declined and both buildings were non-detect 3 months later. The source water in this study had a relatively low conductivity of 440 μS and an alkaline pH of 8.1. Despite these adverse conditions, the case study results showed excellent control of *Legionella* spp.

10.3 | Hotel case study

A boutique hotel with 109 rooms in Northern New Jersey installed CSI treatment on the hot water system in August of 2019 because the hotel had previously experienced several cases of Legionnaires' disease in the facility and other cases of Legionnaires' disease had occurred in the community. Because of the cases, and based on the health department's guidance, the hotel had suspended operations until a successful remediation was able to be completed. Monitoring of the hotel's water system for *Legionella* commenced 60 days following the CSI installation with 10 samples collected from a combination of sinks, bathtubs and showers in the facility. No *Legionella* spp. were detected in the more than 2 years (10 quarters) following the CSI installation despite the low water use during the 2 years of low occupancy due to travel restrictions during the COVID pandemic. The hotel maintained the hot water temperatures at an average of 122.8°F, and copper and silver ion levels averaged 0.72 mg/L and 35.6 μg/L, respectively over the time period (Figure 12).

10.4 | Public housing authority

CSI treatment was installed on the hot water system in a building operated by a government housing authority in a major metropolitan city. The 6-story (excluding basement) building was built in 1941 and routinely operated the hot water system at an average temperature of 111°F (43.8°C) and ranged between 89 and 137°F (31.7–58.3°C); an optimum range for *Legionella* growth. Testing of the hot water system from a variety of bathroom showers, and kitchen and bathroom sinks on 3/14/22 showed detectable *L. pneumophila* in 20 of the 36 samples (Figure 13). The concentrations of *L. pneumophila* ranged from 0.05 to 35 cfu/ml and consisted predominately of serogroup 5. Testing of the municipal water feed to the building was negative. CSI treatment was installed on 3/23/22 and limited testing a month later, and more extensive testing 2 months later, all showed no detections of *Legionella* in the hot water system (Figure 13). The operating temperature of the hot water system did not change.

10.5 | Children's hospital

When one of the nation's most premier children's hospitals first opened in 1991, the facility managers were concerned to find *Legionella* in the building water system. The hospital specialized in treating immunocompromised patients undergoing bone marrow transplants—a population at high risk for nosocomial infections. The first attempt to control the bacteria was to conduct a complete flush of the water system, however, test results continued to come back positive for *Legionella*. The hospital then tried hyperchlorination and performed a superheat and flush, in which water temperatures are elevated above 158°F (70°C) and distal outlets are purged for approximately 30 min. Both of these measures required that patients and staff avoid water use during these treatments to prevent scalding and exposure to high chlorine levels. Both procedures were conducted on a weekly basis and although the procedures temporarily lowered bacterial levels, they failed to eliminate *Legionella* from the system. The hospital suffered its first case of nosocomial Legionnaires' disease in November 1991, only 5 months after opening the newly constructed building. The hospital then turned to the use of a continuous chlorination system in addition to weekly superheat and flush treatments of the water supply. Contamination rates were reduced to 27% of the sites tested, but still failed to eliminate the bacteria and subsequently, a second child developed Legionnaires' disease. CSI was installed in 1993 and the copper and silver ions were able to provide a more consistent control and a lasting residual preventing *Legionella* regrowth, something that periodic hyperchlorination and superheat and flush techniques could not accomplish. Since the installation of CSI treatment, the hospital has

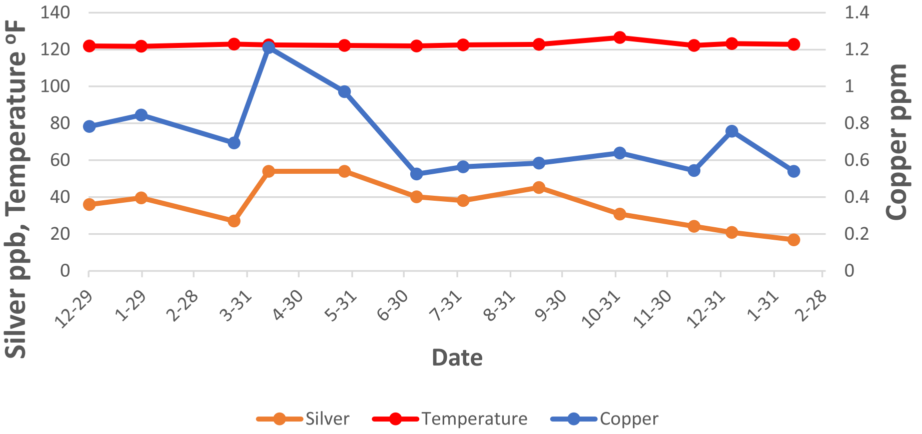


FIGURE 12 Average silver, copper, and temperature levels in an NJ Hotel hot water.

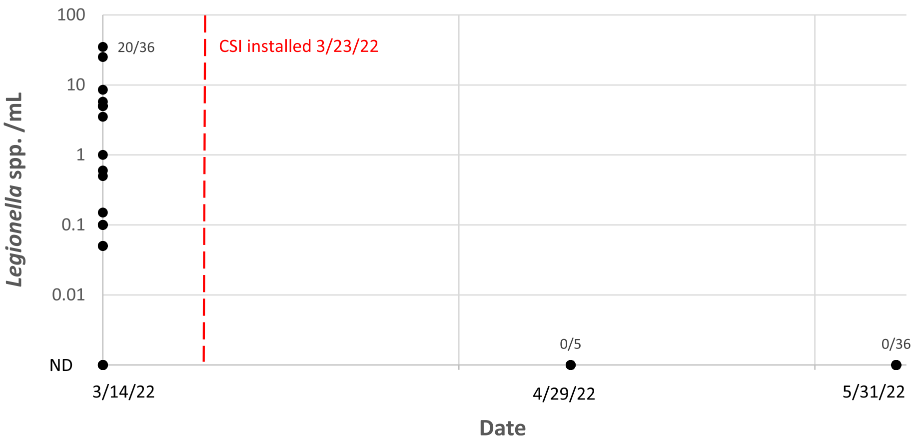


FIGURE 13 *L. pneumophila* occurrence in a public housing authority building. Data labels represent the number of samples positive divided by the total number of samples analyzed.

not had another diagnosed case of Legionnaires' disease and continues to maintain a vigilant program of monitoring and validation to ensure its disinfection program is effective. Despite the low conductivity of the water (45 μS) and high pH (average 9.3; range 8.6–10.1), testing of the water continues to deliver non-detect results for *Legionella* for not only the original building but also for a new facility constructed in 2017 where copper-silver ionization was also installed. The average level of copper ion in the water was 0.30 mg/L (range 0.1–0.6 mg/L), silver averaged 63 μg/L (range 30–144 μg/L) and hot water temperatures averaged 114.5°F (range 112–117°F) (Figure 14). As discussed previously, despite the elevated pH levels, silver ions were still effective in controlling *Legionella* occurrence.

10.6 | Pittsburgh veterans affairs hospital

The Veterans Affairs Pittsburgh Health Care System (VAPHS) first installed CSI in 1994 following multiple cases of nosocomial Legionnaires' Disease (Stout et al., 1998). Previously, the hospital had used the superheat and flush method for *Legionella* control, but cases of Legionnaires' Disease persisted. Use of CSI resulted in a significant reduction in *Legionella* colonization compared to the superheat and flush method (Stout et al., 1998). Five years later, Stout & Yu, (2003) reported the continued success of CSI in managing *Legionella* in the Medical Center, citing a statistically significant ($p < 0.5$) reduction in *Legionella* detections and no cases of hospital-acquired Legionnaires' Disease during the 4 years from 1999 to 2002. However, Stout and Yu left the hospital in 2007 and 2006, respectively, and the maintenance of the CSI system declined. In August of 2012, a patient at the VAPHS was identified with Legionnaires' Disease and additional patients were identified in September, and October (OIG, 2013). A subsequent review by a CDC investigative team identified 22 "probable" or "definite" cases of health care associated Legionnaires' Disease during 2011–2012 period and found that the VAPHS drinking water had widespread colonization of *Legionella*. Five patients died of Legionnaires' Disease. Although the failure of the CSI systems was initially blamed, a review by the Office of the Inspector General (OIG) of the Department of Veterans found that improper operations, lack of maintenance and documentation, lack of flushing, and inconsistent communication and coordination among the staff were responsible for the outbreak. The OIG noted

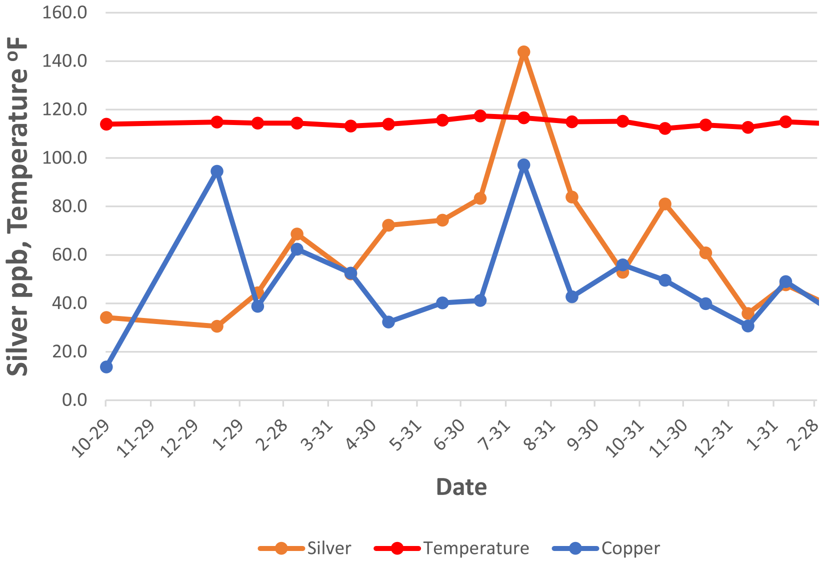


FIGURE 14 Average copper, silver, and hot water temperature in the main children's hospital building.

TABLE 1 Copper and silver ion levels in the VAPHS, 2011–2012.

	Copper-Silver ion levels (mg/L)[a]					
	Building AA		Building BN		Building 7 W	
Date	Copper	Silver	Copper	Silver	Copper	Silver
Jun-11	**0.14**	**<0.005**	2.93	0.08	0.43	0.104
Aug-11	**0.08**	**<0.005**	6.75	0.428	0.32	0.216
Sep-11	**0.17**	**<0.005**	**0.16**	**0.005**	**0.15**	**0.013**
Dec-11	**0.15**	**<0.005**	0.64	0.107	**0.18**	**0.013**
Apr-12	1.56	0.041	0.72	**0.012**	**0.14**	0.031
Jun-12	0.38	0.123	**0.17**	**0.01**	**0.12**	**<0.005**
Aug-12	0.37	0.084	1.31	0.156	**0.17**	**<0.005**
Oct-12	0.2	0.057	0.24	0.026	0.2	**0.015**
Nov-12	ND	ND	0.27	0.02	0.35	0.023

[a] Copper and silver ion levels for samples collected at hot water returns. The target concentration range for copper is 0.2–0.8 ppm; for silver, the target range is 0.02–0.08. Numbers in bold indicate concentrations below the target range. Adapted from OIG, 2013.

that copper and silver levels failed to meet recommended levels (0.2–0.8 ppm for copper and 0.02–0.08 mg/L for silver) in 12 monthly periods for three buildings on the VAPHS campus (Table 1). As outlined above, no disinfection system is going to result in effective *Legionella* control if it is not properly maintained, and operated at target levels. This highly publicized and unfortunate case study illustrates this point.

11 | CONCLUSIONS

As a supplemental treatment within building plumbing systems, the application of CSI to control *Legionella* in building water systems is widespread in over 1000 facilities. However, the scientific literature reveals a mixture of successes and failures. This literature review and presentation of case studies has demonstrated has shown that CSI, as a component of a comprehensive water management strategy, can be effectively used for management of *Legionella* and other waterborne pathogens through the installation of a properly designed and maintained CSI system and the details of the engineering and operation of the system is important to ensure the consistent delivery of copper and silver ions at their target levels.

- Buyers of CSI systems should pay attention to the design and configuration of the electrodes—particularly as they wear.
- The construction of the flow cell, and the adequacy of the power supply are important to deliver the necessary

amperage to achieve the target copper and silver concentrations.

- Copper and silver doses should be flow paced and can be remotely monitored with a web-based interface. An optimum target should be 0.4 mg/L (range 0.2 to 0.8 mg/L) for copper ions and 40 μg/L (range 20 to 80 μg/L) for silver ions and these levels should be confirmed by routine testing, however, ion levels may be decreased once *Legionella* control is established.
- Even the most advanced system will fail if not properly operated and maintained. Regular cleaning of the electrodes should be done to remove the scale that forms normally during use, and the treated pipe system should be routinely flushed to remove sediment and expel stagnant water.
- Whole-building filters can be used to remove any sediment that might come from the potable water supply.
- Although the US EPA recognizes copper and silver as biocides, there are inconsistencies in the state regulatory approval and oversight of CSI installations, so the user should confer with state and local regulatory authorities.
- Water chemistries can impact the operation and performance of CSI systems and should be considered during system planning and commissioning. Particular attention should be on conductivity, temperature, oxygen, flow, pH, dissolved ions including chloride, sulfate, alkalinity, hardness, phosphate, and dissolved organic carbon levels.
- Chemical equilibrium modeling software can assist with this analysis, but case studies show that CSI systems can successfully operate at high pH levels and under a range of conductivity conditions. Several case studies are provided to show the effectiveness of CSI treatment, operations at high pH levels, and the supplementation of CSI to existing chlorine residuals and hot water temperature programs.

The report also highlights some areas for on-going research including any evidence for resistance to sliver inactivation by *Legionella* species and any deposition of copper or silver or changes in corrosion—particularly in systems with years of CSI treatment. Research should also investigate any changes in DBP levels or cytotoxicity under normal CSI operations for both hot and cold-water systems. Despite these opportunities for additional study, abundant existing data shows that the use of CSI for control of *Legionella* and other waterborne opportunistic pathogen occurrences, and disease management, is highly effective and reliable when the units are properly designed, operated, and maintained and used as a component of a comprehensive water management program.

AUTHOR CONTRIBUTIONS

Mark W. LeChevallier: Conceptualization; data curation; formal analysis; supervision; funding acquisition; investigation; methodology; writing – original draft; project administration; writing – review and editing.

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CONFLICT OF INTEREST STATEMENT

The author declares no conflict of interest.

DATA AVAILABILITY STATEMENT

All data will be provided upon request.

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