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Technologies for *Legionella* Control in Premise Plumbing Systems: Scientific Literature Review

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Disclaimer

The U.S. Environmental Protection Agency (EPA) prepared this document to serve as a technical resource for primacy agencies, facility operators and facility owners to use as they evaluate technologies to respond to the risks associated with *Legionella* growth in premise plumbing systems. This document summarizes peer-reviewed scientific literature, reports from nationally and/or internationally recognized research organizations, and guidelines and standards from nationally and/or internationally recognized organizations on the characterization of the effectiveness against *Legionella* of different technologies that may be used to control *Legionella* growth in premise plumbing systems. The document provides information about water quality issues that could result when using the various technologies and summarizes operational conditions for each technology. It also discusses critical risk management approaches to address microbial (including *Legionella*), physical and chemical risks in various parts of the premise plumbing system, such as water management programs (WMPs), hazard analysis and critical control point (HACCP), water safety plans (WSPs) and industrial hygiene principles. This document provides an overview of other strategies that can be used to control *Legionella* growth when addressing a public health threat such as a *Legionella* outbreak. It does not apply to households but rather to commercial and institutional facilities.

This document is not a regulation; it is not legally enforceable; and it does not confer legal rights or impose legal obligations on any party, including EPA, states or the regulated community. While EPA has made every effort to ensure the accuracy of any references to statutory or regulatory requirements, the obligations of the interested stakeholders are determined by statutes, regulations or other legally binding requirements, not by this document. In the event of a conflict between the information in this document and any statute or regulation, this document would not be controlling.

Although this document describes technologies for controlling *Legionella* growth in premise plumbing systems, the information presented may not be appropriate for all situations and alternative approaches may be applicable.

Mention of trade names or commercial products does not constitute an EPA endorsement or recommendation for use.

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Abbreviations and Acronyms

AIHA	American Industrial Hygiene Association
ASTM	American Society for Testing and Materials
ANSI	American National Standards Institute
AOC	Assimilable organic carbon
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
ATP	Adenosine triphosphate
AWWA	American Water Works Association
C	Celsius
CDC	Centers for Disease Control and Prevention
CFR	Code of Federal Regulations
CFU	Colony-forming units
CSI	Copper/silver ionization
CT	Disinfectant residual concentration "C" multiplied by the contact time "T" (C × T)
DBP	Disinfection byproduct
D/DBPR	Disinfectants and Disinfection Byproducts Rule
DPD	N,N-diethyl-p-phenylenediamine
DNA	Deoxyribonucleic acid
DS	Distribution system
ECDC	European Centre for Disease Prevention and Control
ELITE	Environmental *Legionella* Isolation Techniques Evaluation
EP	Entry point to the distribution system
EPA	United States Environmental Protection Agency
EPDM	Ethylene-propylene diene-monomer
F	Fahrenheit
FIFRA	Federal Insecticide, Fungicide and Rodenticide Act
GWR	Ground Water Rule
HAA	Haloacetic acid
HACCP	Hazard analysis and critical control points
HDPE	High density polyethylene
HPC	Heterotrophic plate count
HOCl	Hypochlorous acid
HSE	Health and Safety Executive of the United Kingdom
ICP/MS	Inductively coupled plasma/mass spectrometry
ICU	Intensive care unit
km	Kilometers
LP	Low pressure
MCL	Maximum contaminant level
MF	Microfiltration
mg/L	Milligrams per liter
mJ/cm^2	Millijoule per square centimeter
mM	Millimolar
MP	Medium pressure

MRDL	Maximum residual disinfectant level
NDMA	*N*-nitrosodimethylamine
NF	Nanofiltration
NSF	NSF International
OCl^-	Hypochlorite ion
OSHA	Occupational Safety and Health Administration
PCR	Polymerase chain reaction
POE	Point-of-entry
POU	Point-of-use
PWS	Public water system
qPCR	Quantitative polymerase chain reaction
RO	Reverse osmosis
rRNA	Ribosomal ribonucleic acid
SDWA	Safe Drinking Water Act
SMCL	Secondary maximum contaminant level
spp.	Plural of species
SWTR	Surface Water Treatment Rule
THM	Trihalomethane
TTHM	Total trihalomethanes
µ	Micron (millionth of a weight, distance and/or volume unit)
µg/L	Micrograms per liter
µm	Micrometer
UF	Ultrafiltration
U.S.	United States
UV	Ultraviolet
UVT	UV transmittance
VBNC	Viable but non-culturable
VHA	Veterans Health Administration
WHO	World Health Organization
WMP	Water management program
WSG	Water supply guidance
WSP	Water safety plan

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Preface

This document summarizes peer-reviewed scientific literature, reports from nationally and/or internationally recognized research organizations, and guidelines and standards from nationally and/or internationally recognized organizations. The reviewed literature characterizes the effectiveness of different technologies that may be used to control *Legionella* growth in premise plumbing systems of large buildings (e.g., hospitals, hotels, schools). The U.S. Environmental Protection Agency (EPA) developed this document because the agency recognizes that many species of the genus *Legionella* are a public health threat. While EPA is not promoting or endorsing the use of any of the treatment technologies described in this document as a preferred means of *Legionella* control, EPA recognizes that many facility managers are choosing to install treatment systems to prevent or mitigate *Legionella* growth in premise plumbing systems. The target audience for this document includes, but is not limited to, primacy agencies, facility operators, facility owners and technology developers and vendors. EPA expects this document will improve public health protection by helping the target audience make better informed science-based, risk management decisions to control *Legionella* growth in buildings.

The scientific information presented in this document comes from published literature related to six technologies used for *Legionella* control (chlorine, monochloramine, chlorine dioxide, copper-silver ionization (CSI), ultraviolet (UV) disinfection and ozone). The document provides information about water quality issues that could result when using the various technologies and summarizes operational conditions for each technology. It also discusses risk management approaches for addressing microbial, physical and chemical risks in various parts of the premise plumbing system, such as water management programs (WMPs), hazard analysis and critical control point (HACCP), water safety plans (WSPs) and industrial hygiene principles. This document provides an overview of other strategies that can be used to control *Legionella* growth when addressing a public health threat such as a *Legionella* outbreak.

EPA developed this document in collaboration with state drinking water program representatives. *Legionella* experts at the U.S. Centers for Disease Control and Prevention (CDC) reviewed and provided feedback on portions of the document. State drinking water program representatives and CDC helped to compile the peer-reviewed scientific literature, reports from nationally and/or internationally recognized research organizations, and guidelines and standards from nationally and/or internationally recognized organizations. The scientific information in this document spans from circa 1970 to 2016. Information published in trade journals or popular magazines is not included in this document.

There is not a single one-size-fits-all approach to addressing *Legionella* concerns in premise plumbing systems. A determination of which strategy is best suited for a particular premise plumbing system is case-specific due in part to the complex and diverse nature of premise plumbing systems.

EPA does not recommend the addition of treatment nor the installation of any of the technologies discussed herein, but rather provides technical information regarding the effectiveness of technologies and other approaches for controlling *Legionella* and other microbial contaminants.

In some buildings, risks associated with premise plumbing systems (including *Legionella*) may be addressed without additional treatment.

Stakeholders (e.g., primacy agencies, technology developers and vendors) who are interested in information about the approval process for a new or alternative drinking water treatment technology are advised to consult EPA's Water Supply Guidance (WSG) 90, the State Alternative Technology Approval Protocol (USEPA, 1996). The goal of WSG 90 is to provide a streamlined and consistent protocol to facilitate state approval of new drinking water treatment technologies. WSG 90 is not meant to replace current state plan review and approval processes.

Stakeholders (e.g., primacy agencies, technology developers and vendors) should be aware that pesticide products or devices for drinking water treatment must be in compliance with the Federal Insecticide, Fungicide and Rodenticide Act (FIFRA). EPA's Pesticide Registration Manual (USEPA, no date) provides guidance for applicants seeking to register pesticide products for sale or distribution in the United States and for those interested in selling or distributing pesticides or pesticide devices.

Executive Summary

The U. S. Environmental Protection Agency (EPA) developed this document because it recognizes that many species of the genus *Legionella* are a public health threat. EPA recognizes that many facility managers are choosing to install treatment systems to prevent or mitigate *Legionella* growth in their premise plumbing systems. The target audience for this document includes, but is not limited to, primacy agencies, facility operators, facility owners, technology developers and vendors.

This document summarizes peer-reviewed scientific literature, reports from nationally and/or internationally recognized research organizations, and guidelines and standards from nationally and/or internationally recognized organizations. The reviewed literature characterizes the effectiveness of different technologies that may be used to control *Legionella* growth in premise plumbing systems. Particularly, it focuses on premise plumbing systems of large buildings, such as hotels, hospitals, schools and other buildings with complex plumbing infrastructure.

EPA expects this document will improve public health protection by helping the target audience make better informed science-based risk management decisions to control *Legionella* growth in buildings.

BACKGROUND

Legionella is a bacterium that can be found throughout the world, mostly in aquatic and moist environments (e.g., lakes, rivers, groundwater and soil). The infection caused by *Legionella* is known as legionellosis and occurs primarily in two forms:

1. Legionnaires' disease, which is a type of pneumonia (Fraser et al., 1977).
2. Pontiac fever, which is a milder flu-like illness without pneumonia (Kaufmann et al., 1981; Glick et al., 1978).

The disease can be acquired by inhaling or aspirating aerosolized water or soil (potting soil, compost soil) contaminated with *Legionella* (Travis et al., 2012). No infection associated with animal-to-person contact, consumption of contaminated food or ingestion of contaminated water has been reported. Only one probable case of person-to-person transmission has been reported; it occurred in Portugal (Correia et al., 2016).

While anyone can develop Legionnaires' disease, some common risk factors for developing an infection include age (>50 years), gender (male), smoking habits, existing lung conditions (e.g., asthma, chronic obstructive pulmonary disease), previous use of beta-lactam antibiotics, immunosuppressed or immunocompromised status (e.g., persons receiving transplants or chemotherapy; those with kidney disease, diabetes or AIDS) and recent surgery or intubation (Health Canada, 2013; Viasus et al., 2013; Newton et al., 2010; WHO, 2007; Stout and Yu, 1997). The percentage of fatalities from reported cases of Legionnaires' disease increased with age (> 50 years) and showed a similar pattern for males and females (ECDC, 2016).

Hospitalization costs due to legionellosis in the United States are estimated at $433 million per year (Collier et al., 2012). Fatality rates are estimated to be 5–30 percent (Kutty, 2015). The costs associated with loss of productivity and death are not included in these estimates and are

likely to be significant. Between 3,000 and 4,000 cases of legionellosis are reported to the U.S. Centers for Disease Control and Prevention (CDC) each year; however, the actual number of hospitalized cases is estimated to be between 8,000 and 18,000 (Kutty, 2015; CDC, 2012; Marston et al., 1997), since many cases of pneumonia are empirically treated with antibiotics and never tested for *Legionella* (CDC, 2011; Marston et al., 1997).

Legionella has been found in public water systems. Environmental conditions and processing of the water once it enters a building can lead to the growth of *Legionella*, which could result in increased risks of infection. The CDC has identified environmental conditions within premise plumbing as the leading cause of the *Legionella* outbreaks reported between 2009 and 2012 (CDC, 2015; CDC, 2013).

SCOPE OF THE DOCUMENT

The purpose of this document is to summarize the current body of knowledge on the effectiveness of different approaches to control *Legionella* growth in large buildings.

As a result of *Legionella* outbreaks and the potential for *Legionella* to grow in premise plumbing of buildings, many facility owners or operators have decided to take measures to control or mitigate *Legionella* growth. This document summarizes information on several *Legionella* control technologies, including:

- Risk management approaches (including temperature control)
- Chlorine
- Monochloramine
- Chlorine dioxide
- Copper-silver ionization
- Ultraviolet light
- Ozone

This document provides information on other control technologies that are often used for emergency remediation: superheat-and-flush, shock hyperchlorination and point-of-use filtration.

This document provides a summary of the literature for each technology. The summary includes information about the effectiveness of the technology against *Legionella*, potential water quality impacts that may result from using the technology and operational considerations.

This document describes different types of studies, which include: laboratory, field, premise plumbing and distribution system-based studies. The results from the different types of studies may not be directly comparable to one another given the differences in experimental conditions. Appendix A.1 includes a table that identifies the types of studies conducted for each of the technologies presented in Section 2.3 and Section 3 of this document.

Discussions of *Legionella* control issues related to cooling towers and other systems within the building that do not deliver water for human consumption are not within the scope of this document. The EPA defines “human consumption” as “drinking, bathing, showering, hand washing, teeth brushing, food preparation, dishwashing and maintaining oral hygiene” (40 CFR 141.801 and 63 FR 41940, Aug. 5, 1998).

APPROACH

EPA developed this document in collaboration with state drinking water program representatives. *Legionella* experts at CDC reviewed and provided feedback on portions of this document. State drinking water program representatives and CDC helped to compile the literature referenced in the document, which spans from circa 1970 to 2016. EPA's main criterion for including studies in the "Characterization of Effectiveness against *Legionella*" subsections of Sections 2.3 and 3 was publication in a peer-reviewed document. A draft of this document was released for public review and comment in October 2015. In November 2015, EPA held a public meeting and webinar to seek public input on the draft document. EPA revised the document based on input received during the public comment period. The document was also revised based on input from an independent expert peer review.

SUMMARY OF FINDINGS/CONCLUSIONS

- There is no one-size-fits-all approach to addressing *Legionella* concerns in premise plumbing systems.

- In some buildings, risks associated with premise plumbing (including *Legionella*) in large buildings may be addressed without additional treatment by implementing appropriate risk management approaches (CDC, 2016).

- Facility owners or operators who are considering adding treatment to their building's premise plumbing system may wish to consult with their primacy agency for any specific requirements that may apply before they add any treatment.

- Facility owners or operators may also wish to consult with their water supplier (i.e., public water system (PWS)) to better understand any potential water quality issues before making treatment-related decisions.

- Avoiding dead ends and stagnation and optimizing thermal control of hot and cold water loops in the design of a premise plumbing system could help to mitigate growth of *Legionella*.

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1 Background

1.1 Purpose and Scope

The purpose of this document is to characterize the current body of knowledge regarding the effectiveness of available technologies for the control of *Legionella* growth in premise plumbing systems.[1] The National Research Council (NRC) defines "premise plumbing" as that portion of the distribution system from the water meter to the consumer's tap in homes, schools and other buildings (NRC, 2005). This document focuses on premise plumbing systems of large buildings, such as hotels, schools, hospitals and other similar buildings with more complex plumbing infrastructure. Premise plumbing is used to deliver water intended for human consumption. The U.S. Environmental Protection Agency (EPA) defines water "intended for human consumption" as water used for drinking, bathing, showering, hand washing, teeth brushing, food preparation, dishwashing and maintaining oral hygiene (40 CFR 141.801 and 63 FR 41940, Aug. 5, 1998). Discussions of *Legionella* control issues related to cooling towers are not within the scope of this document. EPA developed this document in collaboration with state drinking water program representatives. *Legionella* experts at the U.S. Centers for Disease Control and Prevention (CDC) reviewed and provided feedback on portions of the document. State drinking water representatives and CDC helped to compile the literature that is summarized and referenced in this document.

The EPA expects this document will improve public health protection by helping the primacy agencies,[2] facility operators, facility owners, technology developers and vendors make science-based risk management decisions to control *Legionella* growth in buildings. It is not EPA's goal to make recommendations for or against the use of any of the technologies discussed in this document.

1.2 *Legionella*: Overview

1.2.1 General Information

The genus *Legionella* currently includes more than 50 bacterial species (abbreviated as "spp.") and approximately 70 distinct serogroups, many of which are considered pathogenic (DSMZ, 2014; LPSN, 2014; Pearce et al., 2012; WHO, 2007; Fields et al., 2002). *Legionella* spp. are gram-negative, rod-shaped bacteria. *Legionella pneumophila* (*L. pneumophila*) was the first species to be described following an outbreak of pneumonia in 1976 among members of the American Legion, who were attending a convention in Philadelphia, Pennsylvania (Fields et al., 2002; McDade et al., 1979). Approximately half of the *Legionella* species described to date have been associated with clinical cases of legionellosis (disease caused by *Legionella*), but it is likely that most legionellae can cause human disease under the appropriate conditions (Borella et al., 2005a; Fields, 1996; Fang et al., 1989). There are several EPA regulations that provide some degree of protection against *Legionella* (see Section 1.4 for additional information).

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[1] For the purposes of this document, the term "*Legionella*" refers to the genus *Legionella* (any species). The plural form legionellae and *Legionella* spp. are also used to denote the genus *Legionella*.

[2] Primacy – States and Indian Tribes are given primary enforcement responsibility (e.g., primacy) for public water systems in their jurisdictions if they meet certain requirements.

Legionellosis is acquired by inhaling or aspirating aerosolized water or soil (potting soil, compost soil) contaminated with *Legionella* (Travis et al., 2012), as opposed to ingestion of contaminated water. Though animals can be infected by legionellae and develop disease, they have not been identified as carriers of legionellae, nor has transmission from animals to humans been documented (Cunha, 2006; USEPA, 1999a). Only one probable case of person-to-person transmission has been reported; it occurred in Portugal (Correia et al., 2016).

1.2.2 Epidemiology and Pathogenesis

Legionellosis includes Legionnaires' disease, characterized by pneumonia (Fraser et al., 1977), and Pontiac fever, a milder flu-like illness without pneumonia (Kaufmann et al., 1981; Glick et al., 1978). Hospitalization is common among Legionnaires' disease patients; inpatient costs in the United States are estimated at $433 million per year (Collier et al., 2012), with a case fatality rate of 5–30 percent (Kutty, 2015). The economic costs associated with loss of productivity and death are not included in these estimates and are likely to be significant.

Legionellosis is a nationally notifiable disease, which means that state health departments report any case that is confirmed by a laboratory to CDC (CDC, 2005). However, many cases of pneumonia that could be Legionnaires' disease are empirically treated with antibiotics and never tested for *Legionella*, so the incidence could be much higher than reported (CDC, 2011; Marston et al., 1997). Between 3,000 and 4,000 cases of legionellosis are reported to CDC each year (Kutty, 2015; CDC, 2012); however, the actual number of hospitalized cases in the United States is estimated to be between 8,000 and 18,000 annually, based on actual cases in two Ohio counties in 1991 (Marston et al., 1997). The wide range in the estimated number of cases is due to inaccuracies in diagnostic testing (Marston et al., 1997).

In the United States, waterborne disease outbreaks associated with *Legionella* have been tracked through the Waterborne Disease and Outbreak Surveillance System since 2001 (Craun et al., 2010). Between 2009 and 2012, CDC reported that *Legionella* accounted for 40 of the 65 drinking water-related waterborne disease outbreaks in the United States, causing 72 illnesses and 8 deaths. CDC identified environmental conditions within premise plumbing systems as the deficiency that caused 32 of the 40 *Legionella* outbreaks (CDC, 2015; CDC, 2013).

Strains of *L. pneumophila* belonging to serogroup 1 are responsible for most cases of Legionnaires' disease in the United States and Europe (Borella et al., 2005a; Yu et al., 2002; Fields et al., 2002; Marston et al., 1994). *L. pneumophila* serogroup 6 may be the second most common serogroup, based on the frequency with which it is isolated from clinical samples (Marston et al., 1994).

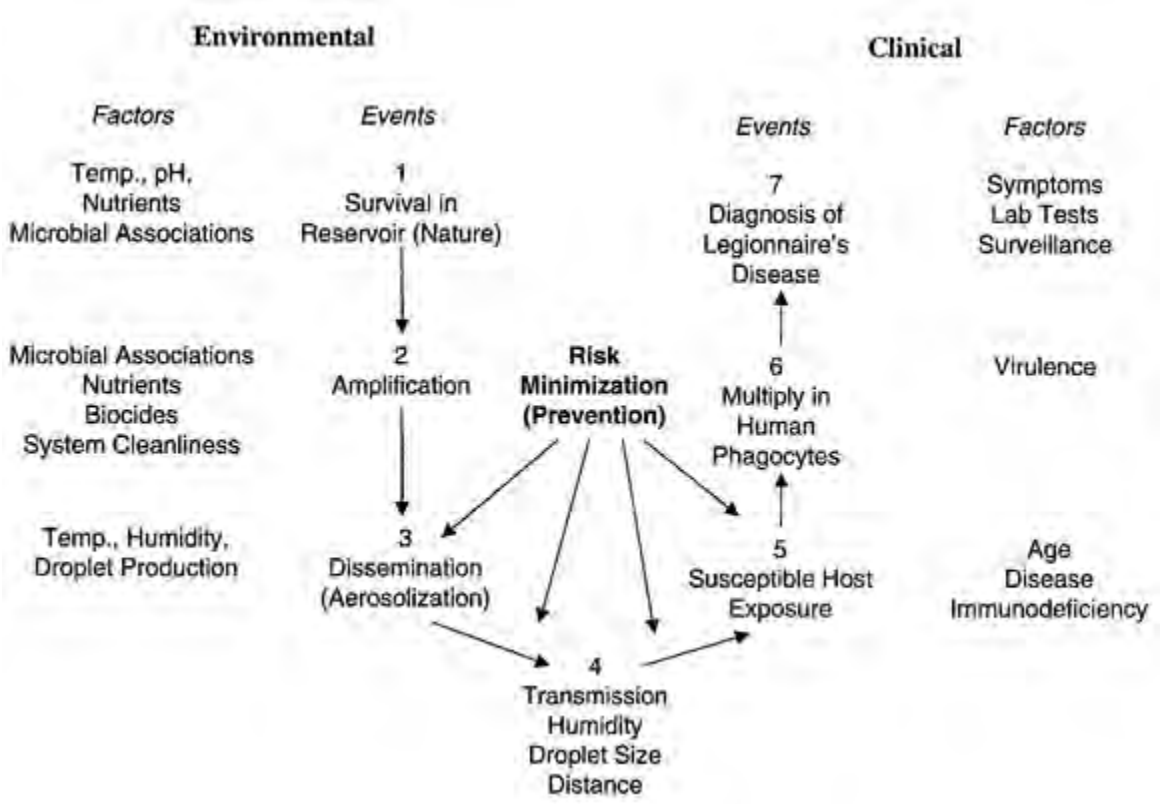
Although *L. pneumophila* causes most cases of Legionnaires' disease, other species can also cause the disease, particularly in hospital-acquired cases. Of the reported non-*L. pneumophila* infections, the most common causes of infection are *L. micdadei*, *L. bozemanii*, *L. dumoffii* and *L. longbeachae* (Fang et al., 1989; Reingold et al., 1984).

While anyone can develop Legionnaires' disease, factors associated with an increased risk of developing infection include age (>50 years), gender (male), smoking habits, existing lung conditions (e.g., asthma, chronic obstructive pulmonary disease), previous use of beta-lactam antibiotics, immunosuppressed or immunocompromised status (e.g., persons receiving transplants or chemotherapy, those with kidney disease, diabetes or AIDS) and recent surgery or

intubation (Health Canada, 2013; Viasus et al., 2013; Newton et al., 2010; WHO, 2007; Stout and Yu, 1997).

Exhibit 1-1 shows different factors and events that could affect the transmission of *Legionella* in environmental and clinical settings. *Legionella* outbreaks can occur when legionellae multiply under particular conditions in water systems and the water is then aerosolized and subsequently inhaled or aspirated by susceptible persons (Donohue et al., 2014; Fields et al., 2002; Blatt et al., 1993; Stout et al., 1985; Fliermans et al., 1981). For these reasons, the presence of *Legionella* is a particular concern in large buildings that house susceptible populations, such as facilities in the healthcare and hospitality industries (Health Canada, 2013; Williams et al., 2013; Buse and Ashbolt, 2012; CDC, 2008; Rusin et al., 1997; Colbourne and Dennis, 1989).

Exhibit 1-1: *Legionella* transmission



Source: ASHRAE, 2000

Premise plumbing systems can be colonized with *Legionella* and transmit the bacteria through aerosols generated from showers, humidifiers and spas associated with hot water distribution systems, as well as from respiratory therapy devices, ultrasonic mist machines, decorative fountains and industrial-use water (Haupt et al., 2012; WHO, 2011a; Carducci et al., 2010; HSE, 2009; Edelstein, 2007; Benin et al., 2002; Stout and Yu, 1997; CDC, 1997; Blatt et al., 1993; Addiss et al., 1989; Muder et al., 1986; Bollin et al., 1985; Dondero et al., 1979; Glick et al., 1978). Aspiration of contaminated aerosols has also been associated with contaminated water and ice (WHO, 2011).

Waterborne disease outbreaks have demonstrated that *Legionella* infections are not limited to premise plumbing systems. Cases have also been linked to ice machines and birthing pools (Public Health England, 2014; Nagai et al., 2003; Franzin et al., 2001; Graman et al., 1997). In addition, several infections have been linked to exposures to potting soil (Whiley and Bentham, 2011; CDC, 2000). Water used in horticultural irrigation is a potential occupational risk (Stojek and Dutkiewicz, 2002). A study by Wallensten et al. (2010) suggests water used instead of windshield washer fluid as another potential route of transmission.

1.2.3 Ecology and Physiology

Fresh water is the major natural reservoir for legionellae. The bacteria are found worldwide in many different natural aquatic environments (e.g., lakes, rivers and groundwater); however, exposure to these sources typically does not result in legionellosis. *Legionella* spp. have also been found to occur in natural soil, potting soil and compost samples (van Heijnsbergen et al., 2014; Travis et al., 2012; CDC, 2000).

Legionellae exhibit several properties that allow them to persist in environmental conditions such as low and high temperatures, presence of disinfectants, low pH, low nutrients and high salinity (Health Canada, 2013; Borella et al., 2005a; Kuchta et al., 1983; Fliermans et al., 1981). Ideal growth conditions are in warm water between 35 and 46 degrees Celsius (C) (95–115 degrees Fahrenheit (F)) (Buse and Ashbolt, 2011; Katz and Hammel, 1987; Wadowsky et al., 1985; Yee and Wadowsky, 1982; Dondero et al., 1979; Glick et al., 1978). High relative humidity increases the viability of *Legionella* spp. in contaminated aerosols (Heng et al., 1995). *Legionella* spp. are considered thermotolerant bacteria, able to withstand temperatures of 50 degrees C (122 degrees F) for several hours (WHO, 2007). This characteristic allows *Legionella* spp. to occur frequently in heated water systems (Taylor et al., 2009). *Legionella* spp. can also survive at temperatures below 20 degrees C (68 degrees F) and even below freezing (Borella et al., 2005a).

Legionella spp. are often found to be protected from adverse environmental conditions as a result of their association with biofilms, as well as their symbiotic and parasitic interactions with other microorganisms. Association with biofilms appears to increase *Legionella's* resistance to disinfectants (Falkinham et al., 2015; USEPA, 2002). Declerck (2010) reported that *L. pneumophila* are associated with biofilms at the air-water interface (i.e., floating biofilms) in addition to the solid-water interface, and these associations can allow *L. pneumophila* to aerosolize and be transmitted over large distances. The association of *L. pneumophila* with many different microorganisms in aqueous environments has been widely demonstrated. Stewart et al. (2012), for instance, demonstrated that *L. pneumophila* could persist in biofilms dominated by other pathogens, such as *Klebsiella pneumoniae, Flavobacterium* and *Pseudomonas fluorescens*. Solimini et al. (2014) noted that the addition of *P. aeruginosa* to a biofilm eliminated *L. pneumophila* in a laboratory co-culture study. They noted that in the absence of *P. aeruginosa*, the addition of heterotrophic plate count bacteria allowed *L. pneumophila* to increase in the biofilm. Although *Legionella* spp. are themselves heat-tolerant, thermotolerant amoebae living in biofilms may provide further protection from heat (Abdel-Nour et al., 2013). However, temperatures greater than 55 degrees C (131 degrees F) may decrease biofilm formation, as other species making up the biofilm cannot survive (van der Kooij et al., 2005; Martinelli et al., 2000).

Conditions that allow growth of *Legionella* in biofilms include long water residence time, the presence of iron (although too much iron can inhibit biofilm formation); the presence of cations

such as calcium, magnesium, zinc and manganese, which facilitate attachment; and temperature. Factors which increase the likelihood of biofilm formation include the presence of nutrients, scale and corrosion, warm water temperatures and long water residence time as occurs in the dead ends of distribution systems and in storage tanks (WHO, 2007). The presence of corrosion and scale increases both the available surface area and the concentration of nutrients and growth factors, such as iron, in the water system. Bacterial systems for attachment (i.e., production of proteins and other substances) are affected by temperature (Abdel-Nour et al., 2013). Of eight *Legionella* species tested, only *L. pneumophila* produces Lcl (protein that contributes to biofilm production), and only *L. pneumophila* was shown to be capable of auto-aggregation (Abdel-Nour et al., 2014). These results support the role of auto-aggregation in the formation of *L. pneumophila* biofilms. Lcl may also contribute to the attachment of *L. pneumophila* to amoebae, facilitating infection of the protozoa.

L. pneumophila also excretes a surfactant that is toxic to other *Legionella* spp., which may prevent or reduce the presence of these species when *L. pneumophila* is present; the surfactant did not affect non-*Legionella* species (Abdel-Nour et al., 2013).

Studies have shown the ability of *Legionella* to parasitize and multiply in several species of protozoa including amoebae and ciliated protozoa (Springthorpe et al., 2014; Cervero-Aragó et al., 2014; Escoll et al., 2013; Buse et al., 2013; Buse and Ashbolt, 2011; Taylor et al., 2009; Fields, 1996), as well as establish symbiotic interactions with other bacteria (Taylor et al., 2009; Rowbotham, 1986; Wadowsky et al., 1985; Bohach and Snyder, 1983; Wadowsky and Yee, 1983; Fliermans et al., 1981). The ability of *Legionella* to parasitize certain protozoa that are commonly found to graze on biofilms in distribution systems is considered particularly important in their ability to survive and grow under adverse environmental conditions (Hoffmann et al., 2014; Escoll et al., 2013; Richards et al., 2013; WHO, 2007; Molmeret et al., 2004; Storey et al., 2004a; Storey et al., 2004b; Thomas et al., 2004; Fields et al., 1984). *Legionella* can parasitize alveolar macrophages (white blood cells that are part of the immune system) in human lungs the same way it parasitizes protozoa (Hoffmann et al., 2014).

Protozoan hosts may be necessary for *Legionella* growth in biofilm in many circumstances. Murga et al. (2001) noted that *L. pneumophila* in a biofilm of *P. aeruginosa*, *K. pneumoniae* and a *Flavobacterium* species did not divide unless the amoeba *Vermamoeba vermiformis* was present. This study was conducted using a continuous flow chamber in which the presence of *V. vermiformis* was not required for survival of *L. pneumophila* but was required for growth. Based on a literature review, Springthorpe et al. (2014) concluded that *V. vermiformis* seems to be the most important amoeba influencing *Legionella* amplification in the field. Although protozoans may be necessary for *Legionella* growth in many cases, Pécastaings et al. (2010) developed a growth medium that allowed growth of monospecies *L. pneumophila* biofilm without the presence of protozoans and without producing free-floating bacterial cells. Andreozzi et al. (2014) suggested that *L. pneumophila* in biofilm may be able to switch to a transmissible or virulent form without the presence of amoebae or other hosts.

Multiple studies suggest that protozoa play a major role in the transmission of *L. pneumophila* and subsequently, legionellosis. For example, there is strong evidence that *V. vermiformis* is associated with *Legionella* outbreaks and helps transmit *Legionella* (Springthorpe et al., 2014). Studies indicate that infectivity may be substantially increased if amoebae infected by *Legionella* are inhaled, as opposed to individual free-living *Legionella* cells (Richards et al., 2013; Newton

et al., 2010; Borella et al., 2005a; Cirillo et al., 1999; Brieland et al., 1996). Infected amoebae may contain hundreds of *Legionella* cells. When these cells are released from the amoebae they could allow a large number of bacteria to reach the lungs (Buse and Ashbolt, 2012; Ohno et al., 2008; Berk et al., 1998; Kwaik et al., 1998; O'Brien and Bhopal, 1993). A study by Berk et al. (1998) also showed that protozoa can release vesicles (membrane-bound, sack-like structures within a cell) of respirable size containing live *L. pneumophila*. The vesicles are resistant to freeze-thawing and sonication (a procedure that uses sound waves to break cells), and the bacteria within the vesicles are highly resistant to biocides. Several studies have also shown that amoebae can serve as reservoirs for many bacteria, including *Legionella*, and these amoebae are resistant to disinfection. This suggests that decreasing the health risk associated with amoebae-resisting bacteria may require physical removal of the amoeba by filtration (Loret and Greub, 2010; Loret et al., 2008). An understanding of the microbial diversity of biofilms and the variables that affect the growth of biofilms is important to managing water-based pathogenic diseases. Proper engineering controls, water treatment and more effective monitoring approaches are needed to help manage risk of exposure to *Legionella* (Ashbolt, 2015).

Another survival mechanism of *Legionella* spp. is their ability to enter a viable but non-culturable (VBNC) state. The VBNC state is part of the normal life-cycle of legionellae as they grow within host cells (Robertson, et al., 2014). Bacteria in a VBNC state fail to grow on culture media, where they would normally grow, yet are still alive and could cause disease (Buse et al., 2013; Oliver, 2010). Numerous chemical and environmental factors have been reported to induce a VBNC state, including nutrient starvation, temperature, high salt concentrations, low oxygen concentration, heavy metals, pipe material and chemical treatment (including water disinfection) (Ducret et al., 2014; Alleron et al., 2013; Buse et al., 2013; Oliver, 2010; Kana et al., 2008; Colbourne and Dennis, 1989). Studies suggest that bacteria in the VBNC state can maintain their infectivity, multiply in their hosts and recover their ability to grow on solid media (Ducret et al., 2014; Alleron et al., 2013; Oliver, 2010; Steinert et al., 1997).

1.3 *Legionella* Occurrence and Risk from the Distribution Systems and Premise Plumbing Systems

Premise plumbing systems have been identified as a source of *Legionella* infection (Stout et al., 1992; Muder et al., 1986). Within healthcare facilities such as hospitals and nursing homes the potable water supply is the most common source of exposure (Lin et al., 2011a). Exposure to legionellae has also been associated with other types of premise plumbing systems (e.g., hotels and other buildings with complex water distribution systems) (Silk et al., 2012; Hung et al., 1993; Tobin et al., 1981a and 1981b). The European Centre for Disease Prevention and Control (ECDC) reports that 58 percent of sampling sites that tested positive for *Legionella* in 2014 were from cooling towers and 26 percent were from water systems, including 66 hot water systems, 31 cold water systems and 184 non-specified water systems (ECDC, 2016).

Legionella spp. are known to be present in finished water from water treatment plants (Lu et al., 2016; Buse et al., 2012) and can persist and grow in the biofilms of municipal water distribution systems (Lu et al., 2016; Wingender and Flemming, 2011; States et al., 1987). Lu et al. (2015) identified diverse *Legionella* spp. including *L. pneumophila*, *L. pneumophila* sg1 and *L. anisa*, in

sediment samples from municipal drinking water storage tanks in 18 locations across 10 states. In the Lu et al. (2015) study, quantitative polymerase chain reaction (qPCR) [3] was used instead of a culture-based approach, and *Legionella* spp. were detected with a frequency of approximately 67 percent. A co-occurrence of *Acanthamoebae* and *Legionella* was observed. Quantitative PCR-based monitoring complements culture-based methods in the presence of disinfectants that affect cell culturability (Bédard et al., 2016).

Schwake et al. (2016) conducted two surveys of tap water, one in small buildings (e.g., single-story homes and businesses) and the other in two hospitals in Flint, Michigan. They found *L. pneumophila* in the two hospitals but not in the small buildings. Schwake et al. (2016) looked at linkages between a *Legionella* outbreak and changes in municipal water quality and operational changes in the distribution system. The study mentions that water utilities may have a role to play in controlling proliferation of pathogens in premise plumbing.

Further, *L. pneumophila* can form biofilm from secreted substances (i.e., extracellular polymeric substances) and can multiply within such biofilms (Mampel et al., 2006). Therefore, biofilms in municipal drinking water systems can be a potential source of water contamination (Wingender and Flemming, 2011) and drinking water from municipal systems can possibly contaminate the premise plumbing systems in hospitals and other buildings with *L. pneumophila* (Donohue et al., 2014; States et al., 1987). Section 1.2.3 discusses optimal conditions that may lead to *Legionella* growth in premise plumbing systems.

Several surveys have found *Legionella* in premise plumbing systems, including in buildings that had not been linked to recognized outbreaks:

- Bartley et al. (2016) traced the epidemiology of two nosocomial (hospital-acquired) cases of Legionnaires' disease at a hospital in Australia. Whole genome sequence analysis was performed on *L. pneumophila* isolates from the patients infected in 2013. The genome sequences were found to be closely related to those of isolates from the hospital water distribution system and to retrospective isolates from a patient infected in 2011.

- Bédard et al. (2016) found *L. pneumophila* in the hot water system of a hospital from 85 percent of sampled taps despite copper treatment. A significant decrease in *L. pneumophila* count by culture was observed following heat shock disinfection. Ongoing corrective measures were implemented, which included increasing the hot water temperature from 55 to 60 degrees C, flushing taps weekly with hot water, removing excess lengths of pipe and maintaining a temperature of 55 degrees C throughout the system. A low level of contamination remained in areas with hydraulic deficiencies.

- Rhoads et al. (2016a) studied *L. pneumophila* trends in controlled, replicated pilot-scale hot water systems with continuous recirculating lines. They demonstrated the potential

[3] A quantitative polymerase chain reaction assay detects a specific gene target known to be associated with a specific genus/species/serogroup. qPCR cannot distinguish between viable and nonviable cells (Donohue et al., 2014).

for thermal control strategies to be undermined by distal taps and corrective mixing. Rhoads et al. (2016b) surveyed a cross-section of green buildings and compared them to conventional buildings. They found increased water age and decreased chlorine and chloramine residuals in the green buildings, as well as increased levels of total bacteria 16S rRNA genes and increased levels of gene markers for *Legionella*. The authors concluded that the elevated water age inherent to achieving the sustainability goals of plumbing systems in green buildings raised concerns with respect to the chemicals and microbiological stability of the water quality.

- Donohue et al. (2014) used two qPCR assays to evaluate incidence of *L. pneumophila* serogroup 1 in 272 water samples collected in 2009 and 2010 from 68 public and private cold drinking water taps across the United States. *L. pneumophila* serogroup 1 was detected in 47 percent of the taps.

- Stout et al. (2007) isolated *L. pneumophila* and *L. anisa* from 14 hospital water systems. They observed high-level colonization of the premise plumbing system (defined as 30 percent or more of the distal outlets being positive for *L. pneumophila*) for 6 of the 14 hospitals with positive findings.

- Borella et al. (2005b) studied *Legionella* in hot water samples of 40 hotels in five Italian cities. They detected *Legionella* in 30 hotels and 60.5 percent of samples. *L. pneumophila* was found in 87 percent of positive samples, and *L. pneumophila* serogroup 1 was in 45.8 percent of positive samples. Of the samples positive for *L. pneumophila* serogroup 1, 75.8 percent had concentrations of 1,000 CFU/L (colony-forming units per liter) or more. The authors found that *L. pneumophila* serogroup 1 presence correlated with soft water and higher chlorine levels (>0.1 milligrams per liter (mg/L)). They also noted that *P. aeruginosa* was less likely to occur at these chlorine levels and more likely to occur in hard water.

- Patterson et al. (1997) sampled hot and cold water outlets in 69 organ transplant units in the United Kingdom for *Legionella* and protozoa. They found *Legionella* in 55 percent of units and *L. pneumophila* in 45 percent. Other *Legionella* (the blue-white fluorescent group, which includes *L. gormanii, L. bozemanii* and others) were detected in 26 percent of organ transplant units. Protozoa of genera known to support growth of *Legionella* were found in 58 percent of units. The authors found a significant association between detection of *Legionella* and the presence of these protozoan genera in the cold water outlets sampled.

- Wadowsky et al. (1985), using tap water from their laboratory, found that naturally occurring *L. pneumophila* multiplied at a temperature between 25 and 37 degrees C (77 and 99 degrees F), at pH levels of 5.5 to 9.2, and at concentrations of dissolved oxygen of 6.0 to 6.7 mg/L. They also noted that *Legionella* growth did not occur in tap water when the dissolved oxygen level was less than 2.2 mg/L. They also observed an association between the multiplication of *L. pneumophila* and non-legionellaceae bacteria, which were also present in the water culture.

- Wadowsky et al. (1982) sampled showerheads, shower pipes and water and sediment collected from the bottom of hot water tanks in 11 buildings, including five homes and three hospitals. *L. pneumophila* serogroups 1, 5 and 6 were isolated from the drinking water fixtures in seven buildings including one of the five homes. *Legionella* spp. were also present in water and sediment in hot water tanks maintained at temperatures from 39 to 54 degrees C (102.2 to 129.2 degrees F), but not found in tanks maintained between 71 and 77 degrees C (between 159.8 and 170.6 degrees F). The authors hypothesized that hot water tanks are the major source and seed of *L. pneumophila* in premise plumbing systems.

- Tobin et al. (1981b) conducted a premise plumbing system survey of 31 buildings including hospitals and hotels, 6 of which were associated with sporadic cases or outbreaks of Legionnaires' disease. For the 6 buildings (hospitals and hotels) associated with cases of Legionnaires' disease, the study found *L. pneumophila* in all of the premise plumbing systems and in the cooling water for each of the 3 buildings with cooling towers. For buildings that had not previously experienced an outbreak, the study found *L. pneumophila* in 4 out of 24 taps or showers, 3 out of 9 cooling towers, and 1 out of 15 storage tanks.

The growth of *Legionella* within a premise plumbing system may be a function of the system's pipe or other plumbing materials, water temperature, water quality and other system-specific factors. Tai et al. (2012) found that copper inhibited biofilm growth at temperatures typically found in hot water systems (20, 37 and 44 degrees C or 68, 99 and 111 degrees F), whereas stainless steel and polyethylene promoted development of biofilm and growth of *L. pneumophila*. Biofilm formation by *L. pneumophila* was found to be inhibited in iron-rich conditions (Hindré et al., 2008). Moritz et al. (2010) found that *L. pneumophila* and *P. aeruginosa* penetrated biofilms grown in cold water on different plumbing materials in the laboratory—ethylene-propylene diene-monomer (EPDM) rubber, silane cross-linked polyethylene, electron ray cross-linked polyethylene and copper. The pathogens, added to biofilms after 14 days, became part of the biofilms in EPDM and the polyethylenes; however, only *L. pneumophila* grew in the copper biofilm, and only in low numbers. In a study of eight different plumbing materials, latex and synthetic rubbers (ethylene-propylene) grew the most extensive biofilm, probably because these materials leach the most nutrients (Rogers et al., 1994).

1.4 Regulatory Context

EPA regulates *Legionella* under the Surface Water Treatment Rule (SWTR). The SWTR has treatment technique requirements to control for *Giardia* and viruses. The SWTR's treatment technique requirements presume that if sufficient treatment is provided to control for *Giardia* and viruses (i.e., 3-log (99.9-percent) inactivation of *Giardia* and 4-log (99.99-percent) inactivation of viruses), then *Legionella* risks will also be controlled. In addition, the Revised Total Coliform Rule (USEPA, 2013a) and the Ground Water Rule (USEPA, 2006a) have treatment technique requirements that address bacteria. Corrective actions related to treatment technique violations may provide some control of *Legionella*. All of these rules apply to public water systems (PWSs).

Premise plumbing systems that do not meet all the exemption criteria in the Safe Drinking Water Act (SDWA) Section 1411 and 40 CFR 141.3 are subject to federal drinking water regulations under 40 CFR Part 141. Adding certain water treatment technologies in a premise plumbing system could impact the chemical and microbial quality of the water and change the regulatory status of the premise plumbing system. The criteria for being a regulated PWS are provided at 40 CFR 141.3. Where there are questions about the application of these criteria, the primacy agency (e.g., the state) typically makes the determination based on these criteria and any relevant site-specific considerations. EPA has issued guidance that primacy agencies may use as they make regulatory application decisions (USEPA, 1976 (Revised in 1998); USEPA, 1990 (Revised in 1998)). States and/or local governments may have drinking water standards for such systems even if federal regulations do not apply.

A determination of which technology is best suited for a particular premise plumbing system is case-specific in part due to the complex and diverse nature of premise plumbing systems and local water chemistry. This document does not specifically recommend the addition of treatment nor the installation of any of the technologies discussed herein; however, it does provide information regarding the operational requirements with which regulated PWSs must comply. This information is included only to provide the reader with a comprehensive understanding of the technologies.

Facility owners or operators who are considering adding treatment to their building's premise plumbing system may wish to consult with their water supplier (i.e., PWS) to better understand any potential water quality issues before making treatment-related decisions. The installation of treatment may also trigger cross connection control measures to protect the water supplier. If a decision to add treatment in the premise plumbing system seems likely, EPA advises facility owners or operators to consult with their primacy agency for any specific requirements that may apply before they add any treatment.

In addition to the drinking water regulations under SDWA, manufacturers of pesticidal treatment technologies used to control *Legionella* and other microbial contaminants need to comply with the Federal Insecticide, Fungicide and Rodenticide Act (FIFRA) requirements, which are independent of the SDWA requirements. Under FIFRA, pesticide devices are regulated, and unless exempt, pesticide products that contain a substance or mixture of substances and that make a pesticidal claim must be registered by EPA prior to sale or distribution. Registration of a pesticide product under FIFRA does not mean that it meets the requirements of SDWA or vice versa. See Questions 7 and 8 in Section 4 for more information.

2 Risk Management Approaches and Technologies to Control *Legionella*

2.1 Overview of Current State of Knowledge

The following sections of this document describe risk management approaches and technologies for controlling *Legionella* growth in premise plumbing systems. The information presented is based on the references reviewed during the preparation of this document; Appendix A.1 lists the references cited in Section 2.3 and the type of study (e.g., lab study, field study, etc.). Section 2.2 introduces risk management approaches as a framework for identifying and prioritizing hazards within a particular premise plumbing system and determining the specific control measures for each priority hazard. Section 2.3 introduces several commercially available technologies that show some effectiveness in mitigating *Legionella* growth in premise plumbing systems, including chlorine, monochloramine, chlorine dioxide, copper/silver ionization (CSI), ultraviolet (UV) light disinfection and ozone. For each technology, the document provides background information, general characterization of its effectiveness against *Legionella*, potential water quality issues and operational conditions (including monitoring frequency and location). This document does not rank or recommend any one technology over another. The information in Section 2.3 is presented in the context of national primary drinking water regulation requirements. The EPA advises facility owners or operators to consult with the primacy agency and/or water supplier about applicability of such requirements to a premise plumbing system.

In Section 3, other strategies (i.e., remediation methods) are discussed, including emergency superheat-and-flush disinfection, shock hyperchlorination and point-of-use (POU) filtration. This section summarizes what is currently known about the performance of these individual technologies for controlling the occurrence of *Legionella* bacteria and other waterborne pathogens in buildings.

In general, all of the technologies discussed in this document have been shown to offer some degree of effectiveness against *Legionella*. However, the long-term eradication of *Legionella* from a premise plumbing system has not been demonstrated consistently with any of these technologies. Complex plumbing systems, such as those found in a multi-story building, may have areas where there is less exposure to disinfectants and heat, which could provide opportunities for bacteria to grow. *Legionella* bacteria may be found in biofilms or in sections of the plumbing system with long water residence times, depending on the pipe materials, water temperature and other system-specific factors. The effectiveness of a technology against *Legionella* growth in biofilm or *Legionella* ingested by amoebae is often cited as a concern. Other studies suggest that disinfectants, disinfection byproducts and other environmental pollutants may induce an increase in antimicrobial resistance of bacteria, including pathogens such as *L. pneumophila* (Ashbolt et al., 2013).

The retention of viable *Legionella* in amoebae cysts is an important factor for risk management of water distribution and premise plumbing systems. Springthorpe et al. (2014) discusses the importance of the association between opportunistic pathogens, such as *Legionella,* and free living protozoa (which include amoebae), and how the protozoa might lead to long term persistence of the pathogens by allowing them to relocate and/or avoid interventions, such as disinfection. Wang et al. (2013) suggest that natural systems may provide conditions, such as an abundance of beneficial microbial diversity, that may help prevent and potentially control the growth of opportunistic pathogens that can be found in engineered environments.

Establishing and maintaining a disinfectant residual throughout the system is critical for the effectiveness of chlorine, monochloramine, chlorine dioxide and CSI treatments. Maintaining a disinfectant residual provides increased protection in the event *Legionella* is released into the premise plumbing system (e.g., sloughing off of biofilm material containing *Legionella*) or enters a premise plumbing system through the PWS distribution system. Ozone and UV disinfection do not produce a disinfectant residual (USEPA, 2007). Therefore, water treated with only these methods, in some cases, may be susceptible to subsequent contamination unless treatment is at the point of use or supplemental treatment is provided. For these reasons, more than one type of treatment or control measure may be necessary to inhibit *Legionella* growth in a premise plumbing system (VHA, 2014). The use of risk management approaches is further discussed in Section 2.2.

The effectiveness of a particular technology is dependent upon building-specific characteristics such as pipe material, age and condition; water usage rates and water age; and water quality parameters (e.g., pH, hardness, organic contaminants, inorganic contaminants, types of waterborne pathogens). Therefore, decision makers may want to consider the specific conditions of each premise plumbing system before making a decision and ensure that the conditions are adequate for the selected approach.

The physical and chemical characteristics of the finished water from water treatment plants may have an impact on the effectiveness of the treatment technologies discussed in this document, albeit not to the same degree. For example, chlorine and chlorine dioxide disinfectant residuals may be difficult to maintain as the water temperature increases due in part to faster reactions with organic materials or pipe surfaces. In contrast, temperature has little impact on the effectiveness of copper or silver ions. The pH of the finished water will impact the effectiveness of chlorine, monochloramine and copper ions, but it will have less of an impact on the effectiveness of chlorine dioxide and silver ions. Other physical parameters (such as turbidity) and chemical constituents (such as chlorides and dissolved organic carbon) can also affect the performance of specific technologies. These issues are covered in more detail in Section 2.3.

Ensuring proper maintenance is a priority for all of the technologies discussed. Failures of technologies put in place to protect the occupants of buildings from exposure to *Legionella* have resulted in outbreaks (CDC, 2013). Safety concerns also exist for most of the technologies (USEPA, 1999b, 1999c). The use of strong oxidants such as chlorine requires proper handling to avoid adverse health risks. The Stage 1 and Stage 2 Disinfectants and Disinfection Byproduct Rules (D/DBPRs) require regulated PWSs using chlorine, monochloramine and chlorine dioxide to maintain disinfectant and disinfection byproduct (DBP) concentrations below the Maximum Residual Disinfectant Level (MRDL) and Maximum Contaminant Level (MCL) to reduce risks from such exposure concerns (USEPA 2006b; USEPA, 1998). Water quality issues are discussed for each technology in Section 2.3.

Unless a *Legionella* outbreak occurs, the decision to employ additional treatment is often difficult for facility owners or operators. Some facility owners or operators choose to install supplemental disinfection treatment systems as a preventative measure based on economic or insurance reasons. The detection of *Legionella* bacteria in tap water samples from a building is likely the most common reason some facilities may choose to add treatment.

The CDC does not recognize a safe level of *Legionella* and recommends certain preventative and corrective actions in health facilities that care for patients who are at higher risk for *Legionella* infection (CDC, 2003). The CDC encourages facility owners or operators to develop and implement comprehensive water safety management plans (CDC, 2016; Garrison et al., 2015). Routine environmental sampling including monitoring for *Legionella* can be performed as part of a building-specific water safety plan (CDC, 2016; ASHRAE, 2015; NYDOH, 2015); however, the CDC notes that there are knowledge gaps in how to use *Legionella* test results as a measure of risk for disease transmission (Demirjian et al., 2015; Garrison et al., 2015). An environmental assessment of the various components of a facility's premise plumbing system can help determine vulnerabilities. These elements commonly include consideration of hot and cold water temperatures, proper service of heating components, water softeners, water fixtures (e.g., showers), spas, water features, humidifiers and cooling towers. In combination with patient surveillance, the environmental assessment and a facility plan will assist in the overall evaluation and control of *Legionella* risks (CDC, 2016; NYDOH, 2015; NYDOH, 2016).

Some limitations and uncertainties associated with the information presented in this document include:

- Some studies were conducted in PWS distribution systems; thus, some results may not be directly applicable to premise plumbing system environments. Likewise, some studies were performed under laboratory conditions that may not necessarily reflect "real-life" plumbing system conditions.

- The information on the infectious dose of *Legionella* is limited due to difficulties in culturing the organism. Many factors can impact the infectious dose, such as the amount of *Legionella* that has been inhaled, the vulnerability of the person and the infectivity of the organism.

- Robust data on qPCR or culture counts in water that lead to disease outbreaks are not available.

- Further clarity is needed regarding the ecology of *Legionella* to help inform the infectious dose question. Legionellae's capacity to colonize biofilms, grow inside protozoa and enter a "viable but non culturable" state increases the uncertainty associated with interpreting monitoring results.

2.2 Risk Management Approaches

2.2.1 Background

Risk management approaches refer to programs that systematically apply risk management principles to reduce biological (including *Legionella*), chemical and physical risks associated with premise plumbing systems. Different names are used throughout the literature to describe risk management approaches. Some examples of risk management approaches include water management programs (WMPs), hazard analysis and critical control point programs (HACCP) and water safety plans (WSPs).

The HACCP concept was established in the early 1960s to ensure the safety of food from microbiological hazards for astronauts working in space (Mortimore and Wallace, 2015).

Beginning in the mid-1970s, HACCP principles were applied to the food industry as a preventative approach for addressing biological, chemical and physical hazards.[4] The process for using this approach in a water system was originally described within a food journal, *Food Control*, in 1994 (Havelaar, 1994).

WSPs were developed by the WHO as a comprehensive risk management approach that uses multiple barriers based on HACCP to ensure public health protection from the source to the tap (WHO, 2011a, 2009, 2007 and 2005).

The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Standard 188 describes a risk management approach that establishes minimum legionellosis risk management requirements for premise plumbing systems. ASHRAE uses the term water management program (WMP) to describe the risk management approach (ASHRAE, 2015).

In 2016, the CDC published guidance to help facility operators and owners develop and implement a water risk management program to reduce risks of *Legionella* growth and spread in premise plumbing systems. The guide can also help the target audience assess and strengthen any water risk management program already in place by providing practical resources to help facility operators ensure that the program is comprehensive, effective and in line with industry standards. The guide also highlights special considerations for healthcare facilities (CDC, 2016).

The American Industrial Hygiene Association (AIHA) recommends using a risk management approach based on industrial hygiene principles and emphasizes proactive routine assessments (AIHA, 2015). The American Society for Testing and Materials (ASTM) International D5952 guidance (ASTM International, 2015) describes a process for identification of cases of Legionnaires' disease or Pontiac fever and appropriate responses to water system contamination.

The Health and Safety Executive of the United Kingdom (HSE) has issued guidance (HSE, 2013) to help employers and landlords comply with the Health and Safety at Work Act as it applies to *Legionella.* The approved code of practice recommends identification and assessment of sources of risk, preparation of a plan, implementation of the plan (including control measures as needed), monitoring, record keeping and designation of a qualified person to assist with compliance.

2.2.2 Applications of Risk Management Approaches

The application of any risk management approach, such as WMP, HACCP or WSPs can be beneficial for the proper management of premise plumbing systems, to protect water quality and public health in general. For more information on WMPs, please refer to the ASHRAE Standard 188 (ASHRAE, 2015). For more information on WSPs, the reader is referred to WHO documents (WHO, 2011; WHO, 2005). For information about the HACCP, WMP and WSP

[4] This approach to food safety was recognized by WHO as being essential for controlling foodborne disease. In 1993, the Codex Alimentarius Commission food code, established by the Food and Agriculture Organization of the United Nations and the World Health Organization (WHO), adopted the HACCP approach (FAO, 1998).

elements, see Appendices A.2 through A.5 of this document. Slight variations can be observed in the elements or steps described by each approach.

EPA does not make any specific recommendation regarding the use of any particular approach. EPA advises facility operators and owners to determine which approaches may be more suitable to their specific needs or whether a combination of approaches is appropriate.

Water system managers have found success in implementing risk management approaches such as WMPs, HACCP and WSPs, similar to the successes seen in the food industry for many years.

- In Iceland, an estimated 68 percent of the population consumes drinking water from systems with WSPs. In a 2008 evaluation of water systems, the authors noted that compliance with drinking water standards improved considerably upon implementation of WSPs (Gunnarsdóttir and Gissurarson, 2008).

- Five full-scale HACCP applications in Australian water distribution systems resulted in reductions in customer complaints and water quality incidents (Martel et al., 2006).

- Researchers in Japan have concluded that HACCP ensures safe and high quality drinking water; they also have proven success with safe water through the previous uses of HACCP for bottled water and ice production (Yokoi at al., 2006).

Risk management approaches have proven to be effective for controlling the growth of significant pathogens in premise plumbing systems, as documented in the following case studies:

- In Minnesota, the Mayo Clinic used HACCP principles to build a water management program for its multi-campus healthcare facilities (Krageschmidt et al., 2014). During implementation of the program, the water management team identified and addressed corrosion and distribution piping design issues and differences in how hazards were controlled between buildings. The clinic found the application of these principles to be a practical and effective approach for improving management of water systems. Forming a multidisciplinary team to develop and implement the plan was productive and increased awareness of water quality issues.

- Evaluations of outbreaks of Legionnaires' disease have shown system deficiencies to be contributing factors to outbreaks (CDC, 2013). The implementation of risk management approaches may identify and help to correct these deficiencies.

- Cristino et al. (2012) reported the successful implementation of risk assessment-based water management plans to control *Legionella* in long-term care facilities. Under baseline conditions, three hot water systems were colonized with *L. pneumophila* and one was colonized with *L. londiniensis*. Specific control measures (e.g., disinfection, environmental monitoring) were implemented in each system, and no cases of hospital-acquired legionellosis occurred during the study period.

- In 2004, a university clinic in Germany adopted the WSP concept. One immediate success this clinic noted was the correction of an infrastructural failure that was identified

during the process. Three years after implementation, two additional improvements were noted: a lowered rate of sepsis in very low birth weight neonates and no cases of nosocomial Legionnaires' disease since implementation (Dyck et al., 2007).

In addition to applying risk management concepts to existing premise plumbing systems, engineers can also use these concepts in the design phase for new premise plumbing systems to help reduce and control hazards (NYDOH, 2016; Krageschmidt et al., 2014; Facility Guidelines Institute, 2014). For example, designing a system to minimize water age and dead-end pipelines may limit the occurrence of waterborne pathogens. Another example is to exclude the use of decorative fountains or other water features that generate aerosols which can be a source of *Legionella* (HSE, 2009). After reviewing published medical literature and external standards pertaining to healthcare facilities, the Veterans Health Administration (VHA) decided to prohibit the use of decorative fountains in its facilities (VHA, 2014). The Facility Guidelines Institute guidance document includes information on the planning, design and construction of hospitals and outpatient facilities and safety risk assessments (Facility Guidelines Institute, 2014). The Occupational Safety and Health Administration (OSHA) recognizes the importance of having controls for premise plumbing systems in place, as under certain conditions any water source can be a source of disease and illness (OSHA, 1999).

2.2.2.1 Temperature Approach for *Legionella* Control

A risk management approach to control *Legionella* in premise plumbing systems may include thermal control of hot and cold water loops in addition to secondary disinfection or other control measures. Thermal control involves maintaining the temperature in hot and cold water systems outside of the range in which *Legionella* can ideally grow (between 35 and 46 degrees C or 95 to 115 degrees F; see Section 1.2.3). Although cold water systems are usually maintained at a temperature less than 20 degrees C (68 degrees F), the temperature can increase during periods of low flow or non-usage (VHA, 2014) as well as during seasonal temperature fluctuations.

A number of entities suggest raising the hot water temperature to a certain level for effective control of *Legionella* growth. To inhibit *Legionella* growth in health care facilities, nursing homes and other high-risk premise plumbing systems, several reports suggest that the hot water temperature be at least greater than 50 degrees C (122 degrees F) at outlets (HSE, 2014; Hruba, 2009; WHO, 2007; Blanc et al., 2005; ASHRAE, 2000; Ezzeddine et al., 1989). Specific suggestions for hot water temperature control include the following:

- Bédard et al. (2016) reported that corrective measures were implemented to control *L. pneumophila* in the hot water system of a hospital. The corrective measures included increasing the hot water temperature from 55 degrees C (131 degrees F) to 60 degrees C (140 degrees F).

- Bédard et al. (2015) found that systems in which water temperature was maintained higher than 60 degrees C (140 degrees F) coming out of water heaters and greater than 55 degrees C (131 degrees F) throughout the hot water system were negative for *L. pneumophila*.

- The United Kingdom's Health and Safety Executive recommends the water heater temperature be maintained at greater than 60 degrees C (140 degrees F), with the temperatures at the outlets reaching 55 degrees C (131 degrees F) in healthcare premises and 50 degrees C (122 degrees F) in other building types within one minute (HSE, 2014).

- The Veterans Health Administration (VHA) requires that all VHA-owned facilities where patients, residents or visitors stay overnight maintain water temperatures at 51.1 degrees C (124 degrees F) or higher in hot water systems to inhibit *Legionella* growth (VHA, 2014).

- In France, regulations for *Legionella* control were recently extended to all public buildings. Target values for water temperature include greater than 55 degrees C (131 degrees F) at the water heater outlet and greater than 50 degrees C (122 degrees F) for any points in the hot water system including points of use and return loops (République Française, 2010).

- Blanc et al. (2005) reported that after increasing the water heater temperature from 50 degrees C to 65 degrees C (149 degrees F), a Swiss hospital experienced a significant reduction in the occurrence of *Legionella*. The temperature at most outlets was greater than 50 degrees C (122 degrees F).

- Darelid et al. (2002) reported that maintenance of a circulating hot water temperature greater than 55 degrees C (131 degrees F), together with a 10-year surveillance program, had successfully controlled Legionnaires' disease in a Swedish hospital. This case study is described in more detail in Section 3.1.1.2.

Circulation of water throughout the hot water distribution system may be necessary for effective thermal control. Accelerating the flow of water in a system has resulted in a noticeable reduction in the concentration of *Legionella* (Ezzedine et al., 1989). Positive *Legionella* detections have occurred at outlets where water circulation was known to be poor (Blanc et al., 2005). Bédard et al. (2015) suggested that nightly shutdown of water recirculation loops be avoided since temperature losses in dead end loops in the system can result in conditions favorable to *Legionella* growth.

To monitor efficacy of thermal control in a WSP, temperature monitoring at the main components in the system and temperature profiling at outlets can be considered to help identify and correct risks (Bédard et al., 2015). Temperature profiling at intermediate locations, such as subordinate flow and return loops feeding different floors of a facility, allows discovery of dead legs and flow rate deficiencies (Bédard et al., 2016). It may be difficult for older buildings to raise their water heater temperature sufficiently to maintain elevated temperatures at outlets (HSE, 2014; WHO, 2007). The efficacy of temperature control in distal low flow areas is important to consider as *Legionella* growth has been shown to be more abundant, with few exceptions, in the hot water system where temperatures are less than 45 degrees C (113 degrees F) (Serrano-Suárez et al., 2013).

Heating water to temperatures necessary to control for *Legionella* can result in greater energy use. While increasing temperature is an effective form of controlling *Legionella* growth, increasing energy use can result in other negative environmental impacts. For more information on how to mitigate other environmental impacts, please visit the ENERGY STAR® website at: https://www.energystar.gov/buildings, and the WaterSense® website at: http://www3.epa.gov/watersense/commercial/index.html.

In addition to increasing energy use, increasing water temperature can increase scalding risks. For most adults, it takes 9 minutes for a second degree burn to occur at 49 degrees C (120 degrees F) while at 51 degrees C (124 degrees F) it takes 3 minutes (Moritz and Henriques, 1947). However, the assessment of scalding risk and selection of hot water temperatures should consider the susceptibility of people at higher risk of scalding including young children, the elderly, the disabled and those with sensory loss (HSE, 2014; VHA, 2014).

Installing automatic compensating mixing valves on outlets can be used to minimize the risk of scalding injury (HSE, 2014; WHO, 2007; ASHRAE, 2000). No scalding injuries were reported with the use of automatic compensating mixing valves over a period of 10 years in a hospital maintaining the temperature at 55 degrees C (131 degrees F) throughout the premise plumbing system (Darelid et al., 2002). However, the blended water downstream of these mixing valves may allow *Legionella* growth; facility managers may want to consider conducting a comparative risk assessment to determine where these valves can be used safely (HSE, 2014). The EPA WaterSense® program recommends using a showerhead and automatic compensating mixing valve that are marked with the same flow rate at a pressure of 45 psi (additional information is available on EPA's website: http://www3.epa.gov/watersense/docs/showerheads_finalsuppstat508.pdf).

Changes in water temperature can affect the efficacy of disinfection treatment, as discussed in Section 2.3. Addition of treatment as part of a risk management approach program of a building could have regulatory implications (see Section 1.4). EPA advises facility owners or operators who are considering adjustments to their premise plumbing system to consult with their water supplier and primacy agency for any specific considerations or requirements that may apply, including plumbing code requirements.

2.2.3 Environmental Testing

Environmental testing involves collecting water samples from the premise plumbing system and analyzing for *L. pneumophila* or other hazards of concern, as well as for water quality parameters (pH, temperature, disinfectant residual) that may indicate efficacy of treatment performance and overall water quality. Environmental testing may be performed as part of an outbreak investigation in order to determine the source and stop transmission of the contaminant or during implementation of a risk management *Legionella* prevention plan such as a WMP, HACCP or WSP (ASHRAE, 2015; AIHA, 2015; Kozak et al., 2013). *Legionella* testing data inform risk assessments and inspection and maintenance programs (Ditommaso et al., 2010).

Stout et al. (2007) found that environmental monitoring followed by clinical surveillance proved to be effective in identifying previously unrecognized cases of hospital-acquired Legionnaires' disease. The study was conducted at 20 hospitals in 13 states. None of the hospitals had

previously experienced endemic hospital-acquired Legionnaires' disease. *L. pneumophila* and *L. anisa* were isolated from 14 hospital water systems. High-level colonization of the premise plumbing system (defined as 30 percent or more of the distal outlets being positive for *L. pneumophila*) was demonstrated for 6 of the 14 hospitals with positive findings. More than 600 patients were evaluated for Legionnaires' disease from 12 hospitals. Hospital-acquired Legionnaires' disease was identified in 4 hospitals, all of which had serogroup 1 in 30 percent or more of the distal outlets.

Demirjian et al. (2015) evaluated medical records and conducted an environmental assessment in a large Pennsylvania hospital to characterize a Legionnaires' disease outbreak that had occurred between 2011 and 2012. The authors also evaluated the contributing factors. As part of the hospital's *Legionella* prevention protocol, they implemented monthly system-wide superheat and flush protocols if at least 30 percent of the distal sites showed *Legionella* growth, "until culture results returned to an acceptable level" (less than 30 percent positive). Based on the 2011–2012 records, the authors found that all definite healthcare-associated cases occurred when sampling results were far below the 30 percent threshold. The authors concluded that definite healthcare-associated cases occurred when only 4 percent of distal sites were positive. In this outbreak, the level of *Legionella* detected was <10 CFU/mL in almost all of the water samples. The authors also noted that quantitative culture results in general have poor precision and can vary within a range of 3-log CFU/mL of viable legionellae. As mentioned in Section 2.1, CDC does not recognize a safe level of *Legionella*.

A review by Allen et al. (2012) also concluded that the 30 percent threshold provides both low specificity (74 percent) and sensitivity (59 percent).

Using *Legionella* test results as a measure of risk for disease transmission may be problematic due to knowledge gaps, including but not limited to, infectious dose, susceptibility of potential hosts and virulence of the strain, as described in the following references:

- CDC and WHO recognize that environmental *Legionella* counts alone cannot predict the probability of human infection from a water system because other factors, such as the exposure dose and level of host susceptibility, contribute to the likelihood of infection (Demirjian et al., 2015; WHO, 2007; Sehulster and Chinn, 2003).

- The lack of reliable and definitive human infectious dose information for *Legionella* makes environmental monitoring results difficult to translate into action levels that can directly reduce human health risks (Demirjian et al., 2015; Buse et al., 2012; Schoen and Ashbolt, 2011; Storey et al., 2004a; Storey et al., 2004b; O'Brien and Bhopal, 1993; Fitzgeorge et al., 1983).

- While detection of *Legionella* in a premise plumbing system may indicate conditions conducive to *Legionella* persistence, some studies suggest that the strains of *Legionella* detected during non-outbreak routine environmental testing may not be the strains usually known to cause disease (Kozak-Muiznieks et al., 2014; Euser et al., 2013; Harrison et al., 2009, Kozak et al., 2009; Doleans et al., 2004).

Current challenges to environmental testing for *Legionella* include the following:

- Despite a number of published procedures for the detection of *Legionella* in water samples, standard culture methods remain limited by their sensitivity and unreliability in detecting a wide range of *Legionella* spp. on a consistent basis (Buse et al., 2012) and detecting VBNC *Legionella* (Oliver, 2010). The time it takes to receive results limits the utility of testing. CDC has established the Environmental *Legionella* Isolation Techniques Evaluation (ELITE) Program for the certification of laboratories that are proficient in *Legionella* isolation by culture (http://www.cdc.gov/legionella/elite.html). This is a voluntary program to identify laboratories that use procedures that are consistent with federal recommendations and meet or exceed industry standards for the recovery of *Legionella.* Culture protocols include water sample treatment and isolate identification and characterization. Other methods, such as molecular (PCR), serological or rapid analysis tests, are not evaluated under this program, and neither are sampling methods.

- Lucas et al. (2011) reported on the results of a pilot study for the ELITE program, which was conducted from September 2008 through March 2009. One of the issues reported with routine sampling is the variability in recovery of legionellae from repeated sampling of sites, as documented by several researchers. In one study of variability, Flanders et al. (2014) evaluated the effects of sample holding and shipping times on *Legionella* test results while taking into account measurement errors. Based on 159 original samples and 2,544 split samples, the authors determined that holding time increased the root mean squared error by 3 to 8 percent.

- There is a lack of standardized protocols for the selection of sampling sites and the frequency of sampling (Lucas et al., 2011; WHO, 2007).

Guidelines on routine environmental testing for *Legionella* vary among different agencies, including the CDC, WHO, AIHA and ASHRAE.

- AIHA (2015) recommended using validated laboratory methods to measure viable *Legionella* bacteria rather than surrogate indicators (e.g., chlorine residual) as part of routine assessments on a semi-annual frequency. AIHA also suggests that *Legionella* testing should be conducted for validation of the plan (i.e., confirming that the plan is effective at controlling the identified hazards), and as part of the outbreak investigation to determine the environmental source of the disease (AIHA, 2015).

- ASHRAE (2015) suggested that the team responsible for developing and implementing the building's risk management plan for *Legionella* control decide whether or not *Legionella* testing should be conducted. Criteria that can support such a decision include: prior history of legionellosis, buildings that serve at-risk or immunocompromised populations, and the incorporation of control limits (i.e., defined values for chemical or physical parameters) into the risk management program (ASHRAE, 2015; HSE, 2014).

- HSE (2014) suggests that monthly *Legionella* testing be conducted in premise plumbing systems that provide treatment with biocides and where water is stored or distribution temperatures are reduced. Monitoring is expected to continue until treatment

effectiveness and control can be confirmed. HSE provides additional guidance on sampling locations in hot and cold water systems.

- VHA (2014) recommends routine environmental testing for *Legionella* in VHA facilities as a way to validate the effectiveness of measures for *Legionella* control.

- The Maryland Department of Health and Mental Hygiene (2000) recommends that water distribution systems within acute care hospitals be routinely cultured for *Legionella* at a facility-specific schedule determined by risk assessment.

Despite the limitations of environmental monitoring, both WHO and CDC acknowledge using *Legionella* testing as one way to verify and validate a WSP (Garrison et al., 2015; WHO, 2007).

If a decision is made to conduct routine environmental testing for *Legionella* as part of a risk management approach, studies recommend that a building-specific sampling plan be developed that specifies the location of sampling sites, the type of samples, the frequency of sampling, the sample collection method and the sample analysis method (AIHA, 2015; Krageschmidt et al., 2014). Ditommaso et al. (2010) concluded that hospitals could adopt a simple and efficient environmental sampling strategy for *Legionella* testing in hot water systems by conducting water sampling including water from the recirculation loop, and excluding biofilm sampling. However, there is no consensus on how many and which types of samples to take (e.g., bulk water or biofilm), nor how often to perform the sampling in order to accurately assess the risk from *Legionella*.

2.3 Technologies

2.3.1 Chlorine

2.3.1.1 Background

Chlorine and chlorine-based compounds are disinfectants that can serve the dual role of efficiently inactivating microorganisms during water treatment, as well as maintaining the quality of the water as it flows from the treatment plant to the consumer's tap. Numerous studies have demonstrated that chlorine effectively kills many disease-causing bacteria and other pathogens (McGuire, 2006).

Chlorine is added to drinking water as elemental chlorine (chlorine gas), sodium hypochlorite solution or dry calcium hypochlorite. Due to safety issues with chlorine gas, many U.S. water systems have switched to sodium hypochlorite for disinfection (McGuire, 2006). Chlorine can be applied by facilities for routine treatment of both hot and cold domestic water; it can be applied to the cold and hot water tanks or to the entire distribution system. However, free chlorine degrades rapidly in hot water systems (Health Protection Surveillance Centre, 2009). Chlorine can also be used at high doses for emergency disinfection of potable water systems through shock chlorination (also called shock hyperchlorination). Shock chlorination is covered in more detail in Section 3.1.2.

For chlorine to be effective against microorganisms, it must be present in sufficient concentration, and must have adequate time to react. For primary disinfection in the municipal water system, this combination of concentration and reaction time is expressed as C (mg/L) × T

(min) or CT. For continued protection against potentially harmful organisms in distribution systems or premise plumbing systems, some level of chlorine needs to be maintained after the initial application. The remaining chlorine is known as residual chlorine.

The addition of chlorine to water creates two chemical species that together make up "free chlorine." These species, hypochlorous acid (HOCl, electrically neutral) and hypochlorite ion (OCl^-, electrically negative), behave very differently. Hypochlorous acid is more reactive than the hypochlorite ion and is also the stronger disinfectant and oxidant. The ratio of hypochlorous acid to hypochlorite ion in water is determined by pH. At low pH (6–7), hypochlorous acid dominates, while at high pH (>8.5) the hypochlorite ion dominates. Thus, the pH of the incoming water may be a factor when deciding upon the use of chlorine as a disinfectant or in the engineering design when addressing issues such as CT for the target organism(s).

Chlorine was first used in the U.S. as a primary disinfectant of drinking water in Jersey City, New Jersey, in 1908 (USEPA, 1999b). Chlorine is widely credited with virtually eliminating outbreaks of waterborne disease in the United States and other developed countries. Among PWSs that disinfect, chlorine is the most commonly used disinfectant (AWWA Disinfection Systems Committee, 2008).

2.3.1.2 Characterization of Effectiveness against *Legionella*

Both laboratory and full-scale studies have been conducted to assess the effectiveness of chlorine against *Legionella*. These studies included a range of physical and chemical water conditions such as chlorine dose and residual levels, temperature and pH. Kim et al. (2002) reviewed available literature on the efficacy of various disinfectants against *Legionella*; findings related to chlorine disinfection include the following:

- Relatively high doses of chlorine (2–6 mg/L) were needed for continuous control of *Legionella* in water systems (Lin et al., 1998a).

- Muraca et al. (1987) reported that chlorine was more effective at a higher temperature (43 degrees C (109.4 degrees F) compared to 25 degrees C (77 degrees F)), but it decayed faster at the higher temperature.

- The association of *L. pneumophila* with protozoa including amoebae required much higher doses of chlorine for inactivation (Kilvington and Price, 1990). Kim et al. (2002) noted that this association with protozoa may explain why chlorine can suppress *Legionella* in water systems but cannot usually prevent its regrowth.

The laboratory studies described below examined the effectiveness of chlorine in inactivating *Legionella* under a range of pH, temperature and chlorine residual levels, although the temperatures tested in some studies were lower than temperatures likely to occur in a building's hot water system. Results showed a wide range of CT values needed for all inactivation levels. While experiments performed to compare efficacy of disinfectants can be useful to demonstrate relative efficacy under the conditions of the experiment, it should not be implied that these values could be used in the field for premise plumbing water systems.

- Gião et al. (2009) found that *L. pneumophila* (strain NCTC 12821) could not be detected using cell culture after exposure to 0.7 mg/L of chlorine in the laboratory for 30 minutes at room temperature (20 degrees C, or 68 degrees F). With a chlorine concentration of 1.2 mg/L, cultivability was lost after 10 minutes. Viability of these cells was only slightly affected when measured using the rapid SYTO 9/propidium iodide fluorochrome uptake assay. When cells that had been exposed to 1.2 mg/L of chlorine for 30 minutes were co-cultured with *Acanthamoeba polyphaga*, they recovered their cultivability after 72 hours.

- Jacangelo et al. (2002) conducted laboratory studies to examine the efficacy of current disinfection practices (e.g., chlorine dioxide, free chlorine and monochloramine) for inactivation of waterborne emerging pathogens including *Legionella*. Chlorine doses of 1.0 to 4.0 mg/L were used. Three different temperatures (5, 15 and 25 degrees C, or 41, 59 and 77 degrees F, respectively) and three different pH (6.0, 7.0 and 8.0) values were examined. The observed CT values for 2-log (99-percent) reduction of *L. pneumophila* at pH 6 ranged from 40 to 500 min-mg/L, depending on the temperature. Observed CT values at pH 7 and pH 8 ranged from 50 to >320 min-mg/L and 25 to >1,000 min-mg/L, respectively. These CT values were at least an order of magnitude higher than those reported by Kuchta et al. (1983) below. The wide range of CT values reported in the literature could be due to different water quality conditions and test protocols used for inactivating *Legionella*.

- Kuchta et al. (1983) studied the effects of various chlorine concentrations, temperatures and pH levels on *Legionella* in tap water. The chlorine residuals used (0.1 and 0.5 mg/L) were consistent with residual levels that would be expected in PWSs. The observed CT value for 2-log (99-percent) reduction of *L. pneumophila* at pH 6 was 0.5 min-mg/L at a temperature of 21 degrees C (69.8 degrees F). Observed CT values at pH 7 and pH 7.6 ranged from 1 to 6 min-mg/L and <3 to 9 min-mg/L, respectively. The authors noted that contact times for the clinical and other environmental sources of *Legionella* were as long as, or longer, than those required for river samples, although long contact times were needed regardless of serogroup or origin. The authors concluded that low chlorine concentrations (0.1 mg/L) allowed *Legionella* to survive for relatively long periods of time. Increasing the total chlorine concentration predictably enhanced the bactericidal effect, resulting in a 99-percent (2-log) kill within the first 5 minutes at a concentration of 0.5 mg/L.

The following pilot studies evaluated the efficacy of chlorine disinfection for inactivating *Legionella* without co-occurring microbial organisms. Both studies were completed using warm water conditions.

- Saby et al. (2005) tested the efficiency of several disinfectants in a hot water system pilot unit. The pilot unit was supplied by tap water pre-heated to 30 degrees C (86 degrees F). *Legionella*-contaminated water was mixed with the tap water before heating. Colonization of the biofilm by *Legionella* was found after seven weeks. After colonization of pipes in the pilot unit, various treatments were tested. Shock hyperchlorination at 50 mg/L of free chlorine residual for 12 hours was found to be very effective in reducing *Legionella* in the water; however, the pipe networks were recolonized in three to four weeks. The authors stated this could be explained by the

inefficiency of shock hyperchlorination treatment on bacteria in biofilms. Continuous chlorine at a dose of 3 mg/L for two periods of four weeks was also examined. The results showed that treatment with chlorine was effective at maintaining low levels of viable bacteria, including *Legionella*. However, a malfunction of the chlorination system resulted in a positive result for *Legionella* within 28 hours. The authors concluded that continuous chlorination allows only for containment of *Legionella* and that technical problems with treatment could result in rapid recolonization. Temperature control at 40 degrees C (104 degrees F) and 55 degrees C (131 degrees F) was also evaluated as part of this study. While temperature control at 55 degrees C was the best technical and economic solution to *Legionella* control, continuous chlorination was also a good solution.

- Muraca et al. (1987) compared chlorine, heat, ozone and UV for inactivating *L. pneumophila* in a model premise plumbing system. A suspension of *L. pneumophila* was added to the system and allowed to circulate. Chlorine disinfection consisted of maintaining a residual concentration between 4 and 6 mg/L through multiple additions of chlorine. Chlorine experiments were conducted at 25 and 43 degrees C (77 and 109.4 degrees F, respectively). Continuous chlorination at a dose of 4 to 6 mg/L resulted in a 5- to 6-log (99.999- to 99.9999-percent) decrease of *L. pneumophila* in six hours. Chlorine disinfection at 43 degrees C (109.4 degrees F) inactivated *L. pneumophila* more reliably and completely than disinfection at 25 degrees C (77 degrees F). Due to thermal decomposition of chlorine residual, more chlorine was needed to maintain a residual of 4–6 mg/L at 43 degrees C (109.4 degrees F) than at 25 degrees C (77 degrees F) (a total of 40 mL of Clorox bleach (5.25 percent chlorine) as opposed to 18 mL). The authors noted that in addition to the higher doses required to overcome residual decomposition, a drop in chlorine levels or failure of chlorination equipment could allow *Legionella* to survive. As a result, the authors concluded that chlorination of hot water systems is more difficult to regulate than that of cold water systems.

The interaction of *Legionella* with co-occurring organisms can affect the efficacy of chlorine for the inactivation of *Legionella.* The following laboratory studies evaluated the effects of co-occurring amoebae on *Legionella* inactivation by chlorine disinfection:

- Dupuy et al. (2011) also investigated the interaction of amoebae and *L. pneumophila*. The authors compared the efficiency of three oxidizing disinfectants (chlorine, monochloramine and chlorine dioxide). These disinfectants were used on three *Acanthamoeba* strains, *L. pneumophila* alone, and *Acanthamoeba* and *L. pneumophila* in co-culture. Chlorine efficiency was evaluated at 30 degrees C (86 degrees F) and at 50 degrees C (122 degrees F). An initial dose between 2 mg/L and 3 mg/L was applied, with a free chlorine residual of 1 mg/L at the end of the treatment. Results were presented as CT (min-mg/L) values. Chlorine was found to inactivate all three strains of *Acanthamoeba* studied, both infected with *L. pneumophila* and not infected. At least a 3-log (99.9-percent) inactivation was obtained for all strains at a CT of approximately 60 min-mg/L. There was a significant difference in inactivation between the strains of *Acanthamoeba* studied, with more than 3-log inactivation found at a CT of less than 10 min-mg/L for one strain. Inactivation efficiency was slightly higher at 50 degrees C (122 degrees F).

- In a study of the interaction of thermotolerant amoebae and *Legionella*, Storey et al. (2004a) evaluated the efficacy of heat and chlorine as disinfectants. The study found that a 2-log (99-percent) reduction in free-living (planktonic) *L. pneumophila* was achieved at 30 minutes with free chlorine concentrations of 1 mg/L and 2 mg/L (at 37 degrees C, or 98.6 degrees F). A 3-log (99.9-percent) reduction of *L. pneumophila* was achieved after 10 minutes with a free chlorine concentration of 10 mg/L (at 37 degrees C, or 98.6 degrees F). The efficacy of free chlorine in the reduction of *Acanthamoeba castellanii* (an amoeba)-bound *L. erythra* was also evaluated. A free chlorine dose of 1 mg/L achieved less than 0.5-log reduction at contact times of 60 minutes or less, whereas a 2 mg/L dose resulted in a 3-log (99.9-percent) reduction at contact times of $\geq$30 minutes (at 37 degrees C or 98.6 degrees F). A free chlorine dose of 10 mg/L and contact time of 10 minutes achieved a 3.2-log reduction. The study found that the interaction of legionellae and *Acanthamoebae* increased the resistance of legionellae to thermal treatment and increased their sensitivity to chlorine. The authors also noted the tolerance of *Acanthamoebae* to high chlorine doses and thermal treatment. Cysts retained their viability at free chlorine levels of 100 mg/L after 10 minutes and at free chlorine levels of less than10 mg/L after 30 minutes. The authors cited a prior study by Kilvington and Price (1990) that found that cysts were able to maintain their viability at free chlorine concentrations of 50 mg/L or less.

- Based on a survey of drinking water supplies in England, Colbourne and Dennis (1989) observed that *L. pneumophila* survived conventional water treatment, including disinfection with chlorine, and retained its ability to colonize pipe surfaces and grow in warm water premise plumbing systems, despite being non-culturable.

The following laboratory studies evaluated the effectiveness of chlorine when biofilm is present:

- Using copper and stainless steel coupons, Cooper and Hanlon (2009) found that mature *L. pneumophila* biofilms (one and two months old) survived a one-hour treatment with 50 mg/L chlorine and continued to grow after treatment, reaching a population of 10^6 CFU per coupon (20-mm diameter disc). The authors also found that planktonic *L. pneumophila* was able to survive and persist at free chlorine concentrations of 0.5 mg/L.

- Loret et al. (2005) expanded on the de Beer et al. (1994) study described later in this section by using a simulated premise plumbing system consisting of pipe loops to compare disinfectants for *Legionella* control in biofilms in premise plumbing systems. The pilot unit also included piping off of the main pipe loop to simulate areas at the ends of a water system (dead ends) with low flow conditions. Tap water and injection of cultured natural *Legionella* strains were used to establish biofilms. Low temperature (35 degrees C, or 95 degrees F) relative to hot water systems and low water velocity, as well as high retention times, were maintained to favor the growth of *Legionella* and biofilms. Each pipe loop was treated with one of the studied disinfectants for three months. The loop receiving chlorine was maintained with a residual dose of 2 mg/L. Each type of disinfectant used in the study displayed rapid initial results in the treated loops, with *Legionella* populations decreasing to undetected levels (less than 500 CFU/L) within three days of treatment, in all cases. However, *Legionella* remained undetected over the

whole study period only with sodium hypochlorite, electro-chlorination, chlorine dioxide and monochloramine. (Ozone and copper/silver allowed occasional re-emergence of detectable *Legionella*.) Ozone, electro-chlorination and chlorine treatments resulted in a reduction of biofilm thickness to below detection limits (<5 µm) after one week. A chlorine dosage rate of 2.5 mg/L removed biofilm better than a chlorine dioxide dosage rate of 0.5 mg/L. Flushing of the dead ends at a rate of 20 percent of the volume per day did not result in a significant reduction in *Legionella*. After a single complete flushing, all simulated dead end sections of piping returned to their initial contamination level within 24 hours. The study concluded that chlorine and chlorine dioxide were the most effective treatment methods in this study (as compared to ozone, monochloramine and copper/silver). The authors suggest that the experimental protocol did not allow for maintenance of a stable product and resulted in insufficient dosing in the pipe loops.

- de Beer et al. (1994) studied the degree to which chlorine penetrates a biofilm based on bulk concentration. For this study, biofilms consisting of *P. aeruginosa* and *K. pneumoniae* were grown for one week, with a maximal thickness of 150–200 micrometers (µm). Transient chlorine concentration profiles were measured in biofilms with a microelectrode that was developed for the investigation and was sensitive to concentrations of chlorine in the micromolar range. The transient chlorine micro-profiles showed slow chlorine penetration into the biofilm, with the rate dependent on the bulk concentration of chlorine. The penetration time exceeded 60 minutes even at the highest concentration tested (0.36 millimolar (mM)). The biofilm matrix, consisting of cells and extracellular polymeric substances, was determined to be a substrate for the chemical reduction of chlorine. Chlorine concentrations measured in biofilms were typically only 20 percent or less of the concentration of the bulk liquid. The micro-profiles showed that following exposure to 2.5 mg/L chlorine for one hour, only the upper 100 µm of the cell clusters was penetrated by chlorine. Findings showed that the limited penetration of chlorine into the biofilm (as determined by penetration depth and rate of penetration) is likely a key factor influencing the reduced efficacy of chlorine against biofilms compared to its effectiveness against planktonic cells. Rapid regrowth after chlorine treatment may have originated from areas within biofilms that are highly resistant to chlorine.

Several studies describe the application of continuous chlorination in hospitals or long-term care facilities in combination with heat treatment and in some cases with shock chlorination.

- Cristino et al. (2012) reported the successful application of various shock disinfection methods (e.g., heat shock, chemical shock with peracetic acid and chlorine dioxide) followed by continuous chlorination for long-term care facilities, including three hot water systems that were colonized by *L. pneumophila* and one hot water system colonized by *L. londiniensis*. No cases of hospital-acquired legionellosis occurred during the study period. Although three of four systems reported that 100 percent of samples were positive for *Legionella* before and after shock treatment, the mean *Legionella* count was reduced by up to 69 percent as a result of shock disinfection. Two years of environmental monitoring after shock disinfection showed that *Legionella* counts either continued to decrease or remained at post-treatment levels.

- Snyder et al. (1990) reported a successful application of heat flushing followed by continuous supplemental chlorination to reduce *L. pneumophila* in a hospital hot water system. Twelve of 74 sampling sites in the hot water system were culture-positive for *L. pneumophila*. Heat flushing (>60 degrees C, or >140 degrees F) at hot water system outlets for 30 minutes alone reduced the number of *Legionella*-positive samples by 66 percent, but within four months, the number of positive samples had increased. Continuous supplemental chlorination was added to the hot water system at a dosage rate of 2 mg/L. After six weeks, the number of *Legionella*-positive samples decreased from 37 percent (43 of 115 samples) to 7 percent (8 of 115 samples). After 17 months of continuous supplemental chlorination, no new cases of legionellosis had occurred.

Several studies explored the potential for *Legionella* to develop resistance to oxidative disinfectants such as chlorine. As described in Section 1.2.3, biofilms and amoeba hosts may act as physical barriers to protect *Legionella* from chlorine or other disinfectants. However, legionellae themselves may easily acquire (and lose) resistance to disinfectants.

- Flynn and Swanson (2014) determined a possible mechanism by which resistance can be conveyed. They found that bacterial DNA segments, which can be transferred from one bacterium to another, can confer resistance to oxidative stress. This resistance could allow *L. pneumophila* to withstand exposure to chlorine, as well as to hydrogen peroxide produced by macrophages or by exposure to antibiotics.

- Kuchta et al. (1985) showed that *L. pneumophila* isolated from hospital hot water systems was less resistant to chlorine after being grown for multiple generations on an agar medium. The contact time required to achieve a 99-percent (2-log) reduction with a chlorine concentration of 0.25 mg/L was 10 minutes on a passaged culture, as opposed to 60 to 90 minutes for *Legionella* cultured directly from tap water samples.

Additional studies that compare the effectiveness of other disinfectants to chlorine to control for *Legionella* are cited in subsequent sections for various technologies.

- In a study of *Legionella* control in full-scale water systems of older hospital buildings in Rome, Italy, Orsi et al. (2014) evaluated the effectiveness of shock hyperchlorination and continuous chlorination over a five-year period. Thirty-eight buildings were studied and 1,308 samples were analyzed for the presence of *Legionella*. Samples were collected before and/or after several chlorination treatment scenarios (before and after shock hyperchlorination, shock hyperchlorination followed by continuous hyperchlorination) from cold water piping, mixed cold and hot piping, and hot water piping. Shock hyperchlorination was described as an applied concentration of 20–50 mg/L, and continuous hyperchlorination was described as a continuously applied concentration of 0.5–1.0 mg/L. The study found a significant association between the presence of *Legionella* in the buildings' premise plumbing systems and the lack of continuous chlorination following shock hyperchlorination. Isolation of *Legionella* was more frequent in mixed water samples (20–40 degrees C (68–113 degrees F)) than in cold or hot water samples. The authors concluded that continuous free chorine levels of 0.5 to 1.0 mg/L resulted in significant reductions in *Legionella* counts in the old hospital water systems. However, this treatment did not completely control *Legionella*.

- Lin et al. (1998a) reported that some hospitals that initially adopted chlorination converted to other methods of disinfection because of failure to control *Legionella* and corrosion of the premise plumbing system. Also, Casini et al. (2014) isolated *Legionella* strains more tolerant of free chlorine from a water system after years of chlorine treatment.

2.3.1.3 Potential Water Quality Issues

Chlorine can react with organics, inorganics and non-halogens in the water to form DBPs (USEPA, 2006b).

Some DBPs have been shown to cause cancer and reproductive effects in lab animals and may cause bladder cancer and reproductive effects in humans (USEPA, 2010). In a simulated premise plumbing system of pipe loops, Loret et al. (2005) found trihalomethane (THM) levels >100 micrograms per liter (µg/L), with an applied chlorine dose of 2 mg/L. For comparison, the EPA drinking water standard for total THM (TTHM) is 80 µg/L. Orsi et al. (2014) noted that special equipment was needed in certain health care settings (e.g., dialysis, neonatal care) to reduce free chlorine and THM levels.

Some DBPs are likely to be carcinogenic to humans by all routes of exposure, while others have suggestive evidence of carcinogenicity (NTP, 2006; USEPA, 2005a). For more information about THMs and potential health effects, see EPA's health criteria document for brominated THMs (USEPA, 2005a).

Continuous chlorination at high levels in premise plumbing systems can result in objectionable tastes and odors along with irritation of skin, eyes and mucous membranes.

Continuous chlorination can contribute to corrosion, with associated leaks, in plumbing systems and may require the simultaneous use of corrosion-inhibiting chemicals. Various corrosion effects have been reported for systems using chlorination:

- Sarver et al. (2011) reported that continuous hyperchlorination increased leaks by up to 30-fold, consistent with extensive laboratory work in soft higher-pH waters.

- Castagnetti et al. (2011) found that no high density polyethylene (HDPE) pipe failure occurred after 2,000 hours of exposure to 2.5 mg/L chlorine.

- Hassinen et al. (2004) studied corrosion in HDPE pipe exposed to chlorinated water (3 mg/L) at elevated temperatures (105 degrees C, or 221 degrees F) and found evidence of polymer degradation on the unprotected inner walls of the pipe.

- Loret et al. (2005) observed similar corrosion marks on mild and galvanized steel coupons installed in pipe loops for various treatment chemicals (chlorine, monochloramine, chlorine dioxide, CSI and ozone).

- Kirmeyer et al. (2004) reported that higher copper corrosion rates are associated with free chlorine compared to equivalent levels of chloramine; however, this is a site-specific issue.

- In a study by Grosserode et al. (1993), leaks first appeared in the copper pipes of a premise plumbing system about two years after installation of the chlorine injectors. Significant deterioration was noted only in the hot water system. The addition of silicate corrosion inhibitors reduced the total number of leaks per year by >80 percent.

2.3.1.4 Operational Conditions

Parameter Conditions Indicating Operational Effectiveness

The efficacy of chlorination is affected by many factors, including chlorine concentration, contact time, pH, temperature, turbidity, buffering capacity of the water, concentration of organic matter, iron and the number and types of microorganisms in the water system (in biofilms and free-living). Lin et al. (2002) reported that 2–6 mg/L of chlorine was needed for continuous control of *Legionella* in water systems. The bactericidal action of the chlorine is enhanced at higher temperatures and at lower pH levels. The anti-microbial efficacy of chlorine declines as pH increases >7, with significant loss of efficacy at pH $\geq$8. However, free chlorine is degraded rapidly at elevated water temperatures, which is a concern for hot water chlorination (Health Protection Surveillance Centre, 2009). Turbidity interferes with the disinfection process by providing protection for organisms; turbidity may need to be reduced prior to disinfection (WHO, 2011b).

Installation Considerations

Chlorine should be stored in the original shipping containers or compatible containers and sited away from direct sunlight in a cool area. Feed rates should be regularly adjusted to account for any losses in chlorine content during storage or handling.

NSF/ANSI Standard 60 certification can help ensure that the quality and effectiveness of water treatment chemicals have been reviewed and found to be acceptable for potable water applications. Some primacy agencies require NSF/ANSI 60 certification. A facility considering application of chlorine gas as the form of chlorine to be used for disinfection would also need to consider potential safety and security concerns. Additional safety procedures will likely be required for personnel training and equipment. Existing OSHA, state or local fire authority regulations may apply and may need to be consulted. Special water system engineering construction standards may also apply for some primacy agencies.

Monitoring Frequency and Location

If a premise plumbing system is a regulated PWS, then the SWTR (USEPA, 1989a) requires that PWSs adding chlorine and using a surface water supply or a ground water supply under the direct influence of surface water monitor for the presence of the residual disinfectant in the distribution system or at the entry point to the distribution system (EP). The disinfectant level

must be at least 0.2 mg/L at the EP and detectable in at least 95 percent of samples collected within the distribution system.

The Stage 1 D/DBPR requires that PWSs that use chlorine maintain a residual disinfectant level of less than 4.0 mg/L as a running annual average (USEPA, 1998).

As stated in the SWTR, PWSs that use chlorine are required to monitor for combined or total chlorine residual or heterotrophic plate count (HPC) bacteria in the distribution system at locations that have been approved by the primacy agency (USEPA, 1989a). These parameters could provide operational information to indicate the need for chlorine dose adjustments, system flushing and managing water age within finished water storage facilities.

Maintenance Needs

Operations and maintenance practices for chlorine disinfection systems include maintenance of an appropriate disinfectant residual, regular system cleaning and flushing, inspections, and water quality monitoring. Newly constructed or rehabilitated piping systems are cleaned and flushed prior to initial disinfection. Routine flushing and water quality monitoring are recommended to assure that adequate disinfectant levels are maintained throughout the premise plumbing system (HSE, 2014).

Since chlorine is recognized as being less effective than other disinfectants at penetrating and controlling established biofilms, chlorination may not be effective if large amounts of scale and sediment are present in the system. These solids are prone to biofilm formation and may need to be removed by cleaning before effective disinfection can be achieved (HSE, 2014). Loret et al. (2005) recommended flushing dead ends daily with disinfected water and removing premise plumbing fixtures and pipes that are rarely used.

2.3.2 Monochloramine

2.3.2.1 Background

The primary use of monochloramine (NH_2Cl) in water systems is to maintain a disinfectant residual in the distribution system. Monochloramine has a more persistent and stable disinfectant residual than chlorine (USEPA, 1994). It causes fewer unpleasant tastes and odors in drinking water than other disinfectants (USEPA, 1994). Monochloramine has a much lower disinfection efficacy than free chlorine (Symons, 1978) and if used as a primary disinfectant it requires a much longer contact time.

Monochloramine is effective for controlling bacterial regrowth and controlling biofilms due to its ability to penetrate the biofilm, although excess ammonia can cause biofilm growth (USEPA, 1999c; LeChevallier et al., 1988a). Monochloramine and chlorine have different mechanisms of action; monochloramine is more specific, and chlorine reacts with a wider array of compounds. When inactivating bacteria in the biofilm, monochloramine is able to penetrate, whereas chlorine may get consumed through reactions that do not occur with monochloramine (Lee et al., 2011; LeChevallier, 1988b). For equivalent chlorine concentrations, monochloramine was shown to initially penetrate biofilm 170 times faster than free chlorine, and even after subsequent application to a monochloramine-penetrated biofilm, free chlorine penetration was limited (Lee et al., 2011). The mechanism of inactivation for chloramine is thought to involve inhibition of proteins or protein-mediated processes such as respiration (USEPA, 1999c).

Monochloramine can be formed by first adding chlorine then ammonia or vice versa. Often ammonia is added after chlorine has acted as a primary disinfectant for a period of time, and the resulting monochloramine is used as a residual disinfectant (USEPA, 1999b; USEPA, 1999c). Although monochloramine is the dominant form produced under conditions typically found in a drinking water system, two other forms of chloramines (dichloramine and trichloramine (nitrogen trichloride)) can also be produced when excessive levels of hypochlorite are present or at low pH levels (USEPA, 1994). Monochloramine is the preferred form of chloramine for use in drinking water treatment due to fewer taste and odor issues and its disinfection efficacy. Monochloramine is a colorless water-soluble liquid (WHO, 2004) with a freezing point at -66 degrees C (-86.8 degrees F).

Monochloramine has been used in the treatment of drinking water for nearly 100 years (USEPA, 2009). It was first used in water treatment in the mid-1910s; the City of Ottawa first used chloramines in 1915 due to the rising costs of bleach. Denver, Colorado, started using monochloramine around the same time as a way to control organisms in the distribution system (Symons, 1978). Its use gained popularity in the 1930s and 1940s but soon declined due to the shortage of ammonia during World War II. The use of monochloramine has been increasing in the past couple of decades due to concerns over DBPs associated with chlorine use (USEPA, 1999c). As of 2009, 1 in 5 Americans were using drinking water treated with chloramines (USEPA, 2009) and this usage rate is projected to increase due to implementation of the Stage 2 D/DBPR (Seidel et al., 2005; USEPA, 2005b).

2.3.2.2 Characterization of Effectiveness against *Legionella*

Laboratory studies have used a wide range of CT values under different water quality test conditions for inactivating *Legionella* by monochloramine disinfection.

- Jakubek et al. (2013) evaluated inactivation of *L. pneumophila* in nuclear power plant cooling circuits with monochloramine formed by combining sodium hypochlorite and ammonia solution with a chlorine-to-ammonia mass ratio of 4.8 (at pH 7.5–8.5 and 25–35 degrees C (or 77–95 degrees F)). The results showed 99.9-percent (3-log) inactivation of environmental strains of *L. pneumophila* with a CT range between 16.14±3.07 min-mg/L and 64.88±19.07 min-mg/L for various strains. The study also found that temperature, pH and initial bacterial concentration affected the ability of monochloramine to inactivate *Legionella*.

- Dupuy et al. (2011) conducted a laboratory study to evaluate the inactivation of both free and intracellular *L. pneumophila* (co-occurring with *Acanthamoeba*) using monochloramine (initial concentration of 0.8 mg/L), chlorine (2–3 mg/L) and chlorine dioxide (0.4 mg/L). Chlorine disinfection studies were conducted at 30 degrees C (86 degrees F) and 50 degrees C (122 degrees F) to simulate cooling tower and building hot water system environments, respectively. Monochloramine and chlorine dioxide disinfection studies were conducted at 30 degrees C (86 degrees F). All samples were treated with disinfectant for one hour and disinfectant residual concentration was measured to calculate CT. Each disinfection treatment was determined to be "efficient" when a 3-log (99.9-percent) reduction was reached. Results showed no difference between the inactivation of both forms of *Legionella* by monochloramine, while the other

disinfectants (chlorine and chlorine dioxide) were not as efficient in inactivating the intracellular *Legionella*.

- Jacangelo et al. (2002) examined inactivation of waterborne emerging pathogens such as *Legionella* by selected disinfectants, including monochloramine. Pre-formed monochloramine was used at a target pH of 7.0. Two different temperatures (5 degrees C (41 degrees F) and 25 degrees C (77 degrees F)) and two different mass ratios of chlorine to ammonia (3:1 and 7:1) were examined. The observed CT values for 99-percent inactivation (2-log reduction) of *L. pneumophila* ranged from >320 to >1,000 min-mg/L. At a water temperature of 5 degrees C (41 degrees F), the CT value at a 3:1 ratio was ≥1,000 min-mg/L and was >320 to >1,000 min-mg/L at a 7:1 ratio. At a temperature of 25 degrees C (77 degrees F), the CT was >630 to >1,000 min-mg/L at a 3:1 ratio and was >320 to >1,000 min-mg/L at a 7:1 ratio. These CT values were similar to CT values for *Giardia* inactivation under the same conditions.

- Donlan et al. (2002) conducted a study with three different monochloramine concentrations (0.2 mg/L, 0.5 mg/L and 1.5 mg/L) and three different contact periods (15, 60 and 180 minutes). All scenarios involved a temperature of 30 degrees C (86 degrees F) and a pH of 7. A monochloramine concentration of 0.2 mg/L was ineffective for all contact periods. At the 0.5-mg/L concentration and 180-minute contact time, 99 percent of *L. pneumophila* was inactivated (i.e., 2-log removal). Using the 1.5-mg/L concentration of monochloramine, 99.9 percent of *L. pneumophila* was inactivated (i.e., 3-log removal) at 60 and 180 minutes contact time.

- A study conducted by Cunliffe (1990) evaluated *L. pneumophila* contact time in a lab-simulated model experiment. This study used a 2.5:1 chlorine-to-ammonia mass ratio prepared by mixing ammonium chloride with sodium hypochlorite at 30 degrees C (86 degrees F) and pH 8.4–8.6. The average CT level for 99-percent inactivation was 15 min-mg/L. The results showed that *L. pneumophila* was more sensitive to monochloramine than *E. coli*.

The wide range of CT values reported in the literature could be due to different water quality conditions and different methodologies used for inactivating *Legionella*.

In another laboratory study, Türetgen (2008) did not calculate CT but determined the resistance of *L. pneumophila* to monochloramine, taking into account both culturability and viability. He found that at 2 mg/L, after 24 hours, an environmental isolate of *L. pneumophila* serogroup 1 could not be cultured. However, viable *L. pneumophila* were detected using epifluorescence microscopy.

One study compared the occurrence of *Legionella* in water distribution systems with chlorine and monochloramine disinfected water. Whiley et al. (2014) measured *Legionella* spp., *L. pneumophila* and mycobacterium avium complex in two drinking water distribution systems: distribution system (DS) 1, using chlorine disinfection, and DS2, using chloramine disinfection. Samples were collected and disinfectant residual was measured four times throughout the year and at different distances from the treatment plant. In DS1, the five sampling sites were located between 5 and 22 kilometers (km) from the treatment plant and had free chlorine residuals in the

range of 0.2 to 1.3 mg/L. In DS2, the five sampling sites were located between 1 and 137 km from the treatment plant and had monochloramine residuals in the range of <0.05 (at a dead-end location) to 3.9 mg/L. All three microbes were detected throughout both distribution systems and at different points throughout the year. The only recurring trend was an increase in microorganisms when the disinfectant residual decreased (for both chlorine and chloramine), especially at dead ends in the system (<0.05 mg/L of monochloramine).

Several laboratory and pilot-scale studies reported on the efficacy of monochloramine in controlling *Legionella* when biofilm is present on pipe surfaces.

- Wang et al. (2012) evaluated the effects of disinfectant (chlorine and chloramine), water age (1 to 5.7 days) and pipe material (polyvinyl chloride, iron and cement) on multiple pathogens, including *Legionella*, using simulated distribution systems. Two sampling events occurred after six and 14 months. The results showed systems treated with chloramines had higher levels of bacteria and protozoa at shorter water ages than systems treated with chlorine. Chloramine concentrations were depleted faster than chlorine due to nitrification of the chloramine. The effects of pipe type on pathogen growth mainly became evident after water age reached 5.7 days, after the majority of the disinfectant residual was depleted. Legionellae were only detected during the 14-month sampling event in bulk water and at lower water ages for chloraminated systems.

- Loret et al. (2005) evaluated disinfectants and their effects on biofilm. They studied *Legionella* control in a pipe loop receiving continuously treated water. Monochloramine treatment was evaluated for one month. The ratio of chlorine to ammonia for monochloramine was 2:1, and an average dose of 0.5 mg/L was used. Planktonic *Legionella* decreased to undetectable levels after three days and stayed undetectable for the remainder of the month. There were no viable *Legionella* in the biofilm after six days of treatment. Biofilm thickness increased with monochloramine treatment after one month of treatment, unlike with the other disinfectants (e.g., chlorine, chlorine dioxide). The study results showed that monochloramine was effective against *Legionella*, but it was not effective in removing the biofilm completely (Loret et al., 2005). Their study concluded that monochloramine was ineffective at inactivating amoeba or biofilm. For a more detailed description of the Loret (2005) study see Section 2.3.1.2.

- Lee et al. (2011) and Pressman et al. (2012) used microelectrodes to investigate the penetration of chlorine, monochloramine, oxygen and free ammonia in nitrifying biofilm. While this research clearly demonstrated that monochloramine had a greater penetration, the authors found this penetration did not necessarily translate to immediate viability loss. Even though free chlorine's penetration was limited compared to that of monochloramine, it more effectively (on a cell membrane integrity basis) inactivated microorganisms near the biofilm surface. The authors also found that the presence of higher free ammonia concentrations allowed a larger biomass to remain active during monochloramine application, particularly the organisms deeper within the biofilm, leading to faster recovery in oxygen utilization when monochloramine was removed. The authors suggested that limiting the free ammonia concentration during monochloramine application would slow the onset of nitrification episodes by maintaining the biofilm biomass at a state of lower activity.

- Donlan et al. (2002) evaluated *L. pneumophila* levels within a biofilm reactor. They found monochloramine to be more effective than chlorine in identical conditions for *L. pneumophila* inactivation, leading the authors to conclude that monochloramine may be more effective for the inactivation of *Legionella* in drinking water distribution systems.

Several studies evaluated the addition of monochloramine for the treatment of premise plumbing systems.

- Coniglio et al. (2015) studied the addition of monochloramine following colonization of two hospital hot water systems with *L. pneumophila* serogroups 3 and 6 (100 percent of samples were positive). Prior to installing monochloramine treatment, the hospital had implemented a combined control strategy which proved to be ineffective:
    - Raised the hot water temperature from 55–60 degrees C (131–140 degrees F) to 65–70 degrees C (149–158 degrees F);
    - Periodic shock hyperchlorination (50 ppm as free chlorine for 1 hour at distal sites),
    - Point-of-use filters (0.2 micron) in high risk areas, changed every 30 days;
    - Addition of hydrogen peroxide (17 mg/L).

  Upon installation of monochloramine treatment, temperature was lowered to 60 degrees C (140 degrees F); pH was between 7.8 and 8.5. Monochloramine treatment began at 3.0 mg/L and after one month was decreased to 2.0–2.5 mg/L. For the next year, legionellae were undetected in all samples, except during one month when the monochloramine generator failed for 15 days. Ammonium, nitrite and nitrate levels did not exceed their limits during the study.

- Baron et al. (2015) noted that treatment of a building's hot water system with supplemental monochloramine resulted in reduced total bacteria count, as well as reduced species diversity, compared to a control (untreated) hot water system that supplied water provided by the PWS. They observed that the reduced bacterial diversity resulted in a lack of competition which could provide an opportunity for *Legionella* to colonize a premise plumbing system, particularly if treatment is interrupted or compromised.

- Baron et al. (2014a) studied the microbial ecology of a hot water system within a hospital following the introduction of monochloramine. Samples were taken three months before and immediately prior to the addition of an on-site monochloramine generation system and then every month for six months after the addition. Monochloramine levels were targeted at 1.5–3.0 mg/L as chlorine. Samples were taken at multiple sites within the hospital's hot water system and analyzed by three methods. The authors observed a shift in microbial ecology immediately after the addition of the disinfectant; the number of operational taxonomic units significantly increased. Microbial ecology variation based on sampling location within the hospital's hot water system (including automatic and standard faucets) increased after the addition of monochloramine. There was a statistically significant increase in the relative abundance of genera associated with denitrification after the addition of monochloramine. Waterborne pathogen-containing genera were also examined. After the addition of monochloramine, an increase in counts

of *Acinetobacter*, *Mycobacterium*, *Pseudomonas* and *Sphingomonas* was observed, using 16S rRNA sequencing. Trends for *Legionella* counts varied but did not show an increase. The sequencing method used was not specific enough to determine changes in individual species; however, a longer-term study of the same facility using cell culture (Duda et al. (2014), described later in the document) noted that *P. aeruginosa* did not increase and *L. pneumophila* serogroup 1 decreased. The addition of monochloramine to the hospital's water system had an impact on the types and amounts of microorganisms found in the hot water system.

- Duda et al. (2014) observed a significant reduction in *Legionella* at distal sites (i.e., sink taps and showers located at distant points in the premise plumbing system) after a monochloramine generation system was installed in a hospital hot water system, replacing a copper-silver ionization system. Monochloramine levels ranged from 1.0 to 4.0 mg/L, measured as Cl_2. The average number of positive sites declined from 53 percent during baseline to 9 percent post-disinfection, based on 29 months of monitoring data including a five-month baseline period and 24 months' data following installation. For most of the post-disinfection study, the percentage of positive distal sites was less than 10 percent. However, during months 10, 12 and 24, the percentage of positive samples was 26, 33 and 22 percent, respectively. During months 10 and 12, the authors noted that nitrate and total ammonia were elevated, suggesting incomplete reaction of chlorine and ammonia and thus decreased formation of monochloramine. The authors noted that no samples tested positive for nitrifying bacteria. The authors also noted increased pH during these months and month 24, greater than the optimal pH for monochloramine disinfection (7.5). *Legionella* speciation changed as a result of monochloramine disinfection. *L. pneumophila* serogroup 1 presence in samples, for instance, decreased from 90 percent of samples during baseline to 49 percent post-disinfection, while L. *bozemanii* presence increased. The authors found that presence of other opportunistic bacteria, such as *P. aeruginosa* and *Mycobacteria*, did not increase post-disinfection.

- Casini et al. (2014) studied monochloramine disinfection at dosage rates of 2–3 mg/L in the hot water system of a university hospital. Compared to disinfection with chlorine dioxide at 0.4–0.6 mg/L, monochloramine performed better because it removed planktonic *Legionella* and it didn't require endpoint filtration. At a monochloramine dosage rate of 2 mg/L, nontuberculous *Mycobacteria* were isolated; increasing the dosage rate to 3 mg/L reduced the culturability of *Mycobacteria*.

- A hospital in Italy added monochloramine treatment to a hot water network within the building using a device to continuously distribute monochloramine (Marchesi et al., 2013; Marchesi et al., 2012). The disinfectant levels were maintained between 1.5 and 3.0 mg/L. Hot water samples were analyzed for *Legionella* spp. and *Pseudomonas* spp. over a one-year period. Both organisms decreased in terms of the number of positive samples. Before the addition of continuous treatment, 97 percent of samples were positive for *Legionella*. After treatment, approximately 13 percent of samples were positive for *Legionella*. The authors concluded that, based on this study, continuous injection of monochloramine in a building hot water system has potential for controlling *Legionella* (Marchesi et al., 2012). Marchesi et al. (2013) continued the study for a total of 36

experimental months with the same parameters for monochloramine and confirmed that *Legionella* control with monochloramine was rapid, as 7 out of the 8 positive samples occurred within the first eight months of the total 36-month experimental period. The eighth positive sample occurred at 15 months, when the monochloramine dosage rate decreased below 1 mg/L. Use of monochloramine did not increase chlorite levels and nitrification did not occur. The authors suggested that a monochloramine concentration between 2 and 3 mg/L should be maintained to assure a *Legionella* concentration less than 10^2 CFU/L.

Several studies evaluated *Legionella* occurrence in premise plumbing systems receiving water from a PWS, and no additional treatment was provided at the buildings.

- Weintraub et al. (2008) evaluated water and biofilm samples from hot water systems in 53 buildings in San Francisco before and after the PWS switched to monochloramine for residual disinfection in February 2004. Chlorine was used for primary disinfection throughout the study period. The total chlorine level in finished water was 0.6 mg/L on average prior to conversion and 1.97 mg/L on average in 2004 following conversion. Samples were collected from each building six times during the two-year study period—three samples before and after the conversion to monochloramine. Sampling results showed that 60 percent of hot water systems and 72 percent of buildings contained *Legionella* before conversion to monochloramine compared to 4 percent of hot water systems and 9 percent of buildings after the conversion. After the conversion to monochloramine, there was an approximate 10-fold increase in the concentration of total chlorine in the buildings' hot water systems. Also, prevalence of *Legionella* decreased by 96 percent in POU outlets (Weintraub et al., 2008).

- Flannery et al. (2006) compared *Legionella* colonization of hot water systems for two years to determine if a conversion from chlorine to monochloramine in the municipal water supply would reduce *Legionella* levels in the building hot water system. The results showed 60 percent colonization of the hot water system before conversion and 4 percent colonization after the conversion. After switching to a disinfectant with a more stable residual, higher concentrations of total chlorine were measured within building hot water systems. The authors concluded that increasing the amount of water supplies disinfecting with monochloramine might reduce the incidence of Legionnaires' disease.

- Moore et al. (2006) evaluated *Legionella* colonization within building hot water systems in Pinellas County, Florida, before and after the wholesale PWS had converted from chlorine to monochloramine for residual disinfection treatment. *Legionella* colonization of premise plumbing systems decreased from 19.8 percent (19 of 96 buildings) to 6.2 percent (6 of 96 buildings). The samples in this study were taken a few months before and a few months after the conversion to monochloramine.

- Heffelfinger et al. (2003) concluded that hospital water systems using a monochloramine disinfectant residual were at a lower risk of Legionnaires' disease cases than systems using a chlorine residual, based on survey data. Out of 459 surveys sent, 166 hospitals in the U.S. responded (a 36-percent response rate). Of the 166 survey respondents, 38 (25 percent of survey respondents) were selected as case studies because they had reported

definite cases of Legionnaires' disease in the period 1994 to 1998 or outbreaks of hospital-acquired Legionnaires' disease in the period 1989 to 1998, and they had not changed their water disinfection practices during the study period. Six of the 38 case study hospitals (16 percent) received municipal water treated with monochloramine for disinfection. Hospitals reporting occurrence of Legionnaires' disease were more likely to have used supplemental disinfection beyond that supplied by the municipal water. Of the 128 survey respondents that reported no cases of Legionnaires' disease during the study period, 59 (46 percent) used monochloramine disinfection. The hospitals supplied by drinking water with a monochloramine disinfectant residual were less likely to have definite cases or outbreaks than hospitals with chlorine disinfectant residuals (adjusted odds ratio: 0.20; 95-percent confidence interval: 0.07–0.56).

- Kool et al. (2000) conducted a case control study comparing disinfection methods in water supplied to hospitals with reported Legionnaires' disease (32 hospitals) with the disinfection methods used in water supplied to control hospitals (48 hospitals) with no reported disease. They found that hospital water systems supplied with water treated by chlorine were more likely to have reported an outbreak of Legionnaires' disease than hospitals supplied with water treated by monochloramine (odds ratio 10:2 and 95-percent confidence interval: 1.4–460). The authors infer that 90 percent of the outbreaks might have been prevented had the residual used in the case hospitals contained monochloramine (Kool et al., 2000; Kool et al., 1999). The cases in this study were based on previous records of infections and not on *Legionella* measurements in the water supply (Kim et al., 2002).

2.3.2.3 Potential Water Quality Issues

Potential water quality issues associated with monochloramine include corrosion, formation of DBPs and nitrification. The use of monochloramine can cause corrosion of the pipes and materials used in water systems. Corrosion can occur in two forms, including pitting and a more uniform thinning of pipe surfaces (Kirmeyer et al., 2004). Zhang et al. (2002) studied the effects of monochloramine on uniform corrosion of copper coupons at pH values of 7.6 to 8.4 and observed that the corrosion mechanism may be significantly affected by the presence of monochloramine.

Kirmeyer et al. (2004) also reported that chloramine can attack rubber and plastic components in a water system and that 43 percent of utilities surveyed experienced an increase in degradation of rubber materials after chloramine disinfection was implemented. Loret et al. (2005) observed corrosion marks on mild and galvanized steel coupons installed in pipe loops for monochloramine treatment that were similar to corrosion marks on coupons exposed to other disinfectants (chlorine, chlorine dioxide, CSI and ozone), except the coupons exposed to CSI also had copper deposits.

Monochloramine can react with pipe scale differently than other disinfectants, resulting in lead leaching in system materials containing lead (Edwards and Dudi, 2004). However, corrosion may not occur in all cases. Duda et al. (2014) found a temporary increase in copper and silver concentrations during the first few months of their 18-month study, which they felt was due to the release of copper and silver ions that had accumulated during prior treatment with copper-silver ionization. Corrosion control and maintenance of premise plumbing systems will be

important to consider before adding disinfectants. Further research is needed to evaluate the interactions of disinfectants with water chemistry and piping materials in a premise plumbing system and to better understand the effects of these interactions on the efficacy of pathogen inactivation (Rhoads et al., 2014). Water temperature, pH and disinfectant concentration affect corrosion rates.

Additional information about chloramines and chloramine-related research, and answers to questions raised by the public related to exposure to chloramines can be found at EPA's website: http://www.epa.gov/dwreginfo/basic-information-about-chloramines-and-drinking-water-disinfection. Monochloramine has the ability to react with organics, inorganics and non-halogens in the water to form DBPs (USEPA, 2006b).

Although chloramination significantly reduces formation of some DBPs associated with chlorine disinfection, such as THM and HAAs, its usage can contribute to the formation of other DBPs such as nitrosamines. For more information regarding nitrosamines please see the *N*-nitrosodimethylamine (NDMA) fact sheet (USEPA, 2014a) at EPA's website: http://www2.epa.gov/sites/production/files/2014-03/documents/ffrrofactsheet_contaminant_ndma_january2014_final.pdf. NDMA does not currently have a health-based standard under the Safe Drinking Water Act. EPA's Integrated Risk Information System (IRIS) has classified NDMA as a probable human carcinogen based on the induction of tumors in rodents and non-rodent mammals.

Nitrification is a potential problem for utilities that utilize chloramines as a disinfectant and may occur when finished water contains excess ammonia and low chloramine residual (Kirmeyer et al., 2004). Areas of the distribution system with higher water age and warmer temperatures are more susceptible to nitrification. Nitrification is a microbiological process that oxidizes ammonia to form nitrite and nitrate. Increased nitrate levels provide nutrients for the growth of nitrifying bacteria. Nitrification can also degrade the aesthetic quality of the water resulting in taste and odor issues as well as particles in the water (AWWA, 2013). Breakpoint chlorination can occur due to imbalances in chlorine and ammonia concentrations, resulting in the formation of nitrate, nitrogen chloride and nitrogen gas. Once nitrification occurs, maintaining monochloramine disinfectant residual becomes very difficult within the nitrified areas of the distribution system, allowing pathogenic organisms that may be present in biofilm or pipe scale to proliferate. The American Water Works Association's (AWWA) Manual M56 recommends that any utility using chloramines develop and implement a nitrification control plan (AWWA, 2013).

Monochloramine can inhibit biological growth on filters, which could be positive in that it helps keep the filters clean, but this inhibition can also reduce biodegradable dissolved organic carbon removal, a problem if the filters were put in place for that purpose. Although nitrification may be an issue for public water distribution systems, several studies in hot water premise plumbing systems found no evidence of nitrification (Coniglio et al., 2015; Duda et al., 2014; Marchesi et al., 2013, 2012).

Converting disinfection to monochloramine can have an impact on organisms other than *Legionella*. A study by Moore et al. (2006) found that, in addition to *Legionella*, premise plumbing systems were colonized with *Mycobacteria* before and after a conversion from chlorine to monochloramine in the PWS. The proportion of buildings colonized with

Mycobacteria increased from 19.1 percent during the chlorine phase to 42.2 percent after the conversion to monochloramine. The number of samples within the distribution system containing detectable levels of coliform increased from two samples during the chlorine phase to twenty samples after the conversion (Moore et al., 2006).

Pryor et al. (2004) saw similar results in a study conducted in Florida. After conversion to monochloramine, *Mycobacteria* increased, total coliforms and heterotrophic bacteria levels increased, and nitrification occurred in the storage tanks. Facility owners or operators who consider treating water with monochloramine to control for *Legionella* should be cognizant of potential unintended consequences, such as increases in *Mycobacteria* and other waterborne pathogens, and take the necessary protective measures to protect public health. Gomez-Alvarez et al. (2012) also observed that *Legionella*-like genes were more abundant under chlorine treatment, while mycobacterial genes were more abundant under monochloramine treatment conditions in laboratory simulated distribution systems.

2.3.2.4 Operational Conditions

Parameter Conditions Indicating Operational Effectiveness

The normal dosage rate for monochloramine is between 1.0 and 4.0 mg/L.

The case studies cited earlier generally support maintaining a chloramine residual in the premise plumbing system in the range of 1 to 2 mg/L as an effective means for containing biofilm growth, minimizing *Legionella* colonization and preventing outbreaks. As such, premise plumbing system practices such as maintenance of appropriate pH, maintenance of chlorine-to-ammonia ratios, flushing and frequent monitoring to demonstrate residual maintenance on an ongoing basis are essential. The current practice is to use a chlorine-to-ammonia ratio of 3:1 to 5:1 to produce monochloramine. The amount of organic nitrogen in the water prior to addition of ammonia will also affect how much ammonia is needed to reach the desired ratio (USEPA, 1999c).

The rate of reaction for the conversion of chlorine to monochloramine is sensitive to pH and can also be affected by contact time and temperature. The optimum pH range for formation of monochloramine is 7.5 to 9 (WHO, 2004). Monochloramine is relatively stable under varying temperatures once formed. Cunliffe (1990) evaluated monochloramine decay at two different temperatures. Water incubated at 55 degrees C (131 degrees F) showed a loss of residual after 50 hours, from 1.3 to 0.35 mg/L. After five days at 30 degrees C (86 degrees F), the concentration dropped from 1.3 to 0.8 mg/L.

Installation Considerations

Guidelines for design and implementation of chloramination systems include the following:

- AWWA M56 Manual, Nitrification Prevention and Control in Drinking Water. Second Edition (AWWA, 2013).
- Simultaneous Compliance Guidance Manual for the Long Term 2 and Stage 2 DBP Rules (USEPA, 2007).
- The Water Research Foundation manual Optimizing Chloramine Treatment (Kirmeyer et al., 2004).

- Alternative Disinfectants and Oxidants Guidance Manual (EPA 815-R-99-014) (USEPA, 1999c).

Monitoring Frequency and Location

The SWTR (USEPA, 1989a) requires all PWSs that use surface water or ground water under the direct influence of surface water and that choose monochloramine as a disinfectant to monitor for the presence of a disinfectant residual in the distribution system and at the EP. The disinfectant level must be at least 0.2 mg/L at the EP and detectable in at least 95 percent of samples collected within the distribution system.

The Stage 1 D/DBPR also requires PWSs that use monochloramine to maintain a residual disinfectant level running annual average of less than 4.0 mg/L (USEPA, 1998).

PWSs that use chloramines are required to monitor for combined or total chlorine residual or HPC in the distribution system at locations that have been approved by the primacy agency. These parameters could provide operational information to indicate the need for chloramine dose adjustments, system flushing and water age management within finished water storage facilities.

Monochloramine can be measured by amperometric titration (Symons, 1978), N,N-diethyl-p-phenylenediamine (DPD) ferrous titrimetric, DPD colorimetric methods (USEPA, 1999c) and commercially available adapted indophenol methods (Hach MonochlorF) (Lee et al., 2007). EPA has approved multiple methods for measuring combined chlorine as well as total chlorine. A list of approved methods is available through EPA's website (USEPA, 2014b).

Other monitoring should be conducted to identify the onset of nitrification, which is common in systems that use chloramination. Kirmeyer et al. (2004) recommended monitoring HPC, chloramine residual, ammonia, nitrate and nitrite to detect nitrification in the distribution system. A system-specific monitoring plan should be developed to identify sampling locations, parameters and sampling frequency.

Maintenance Needs

Operating and maintenance practices for chloramine disinfection systems include maintenance of an appropriate disinfectant residual, regular system cleaning and flushing, inspections and water quality monitoring. Newly constructed or rehabilitated piping systems are cleaned and flushed prior to initial disinfection. Routine flushing and water quality monitoring are recommended to assure that adequate disinfectant levels are maintained throughout the premise plumbing system (HSE, 2014).

Many systems using monochloramine as a residual disinfectant periodically use free chlorine to control biological growth that may have occurred in the distribution system or on equipment (AWWA, 2013).

Approaches for preventing nitrite and nitrate formation within the distribution system include decreasing water age through flushing or operational changes, increasing the pH, decreasing temperature, decreasing total organic carbon concentration, increasing monochloramine

residuals, increasing the chlorine-to-ammonia ratio and decreasing the excess ammonia concentration (USEPA, 1999c).

2.3.3 Chlorine Dioxide

2.3.3.1 Background

Chlorine dioxide is a water-soluble gas that can easily diffuse through cell membranes of microorganisms. It has been found to be superior in penetrating biofilms as compared to chlorine (Lin et al., 2011b). Studies have shown that chlorine dioxide is an effective disinfectant (when used correctly) for inactivating certain bacterial pathogens (e.g., *E. coli*, *Salmonella*), viruses (e.g., poliovirus, coxsackie virus) and protozoan pathogens (e.g., *Giardia*) (USEPA, 1999c). It has a high oxidation potential). Its use as a biocide can be maintained over a wider pH range than can the use of chlorine or CSI (Lin et al., 2011b).

Chlorine dioxide was first used as a disinfectant in the early 1900s at a spa in Belgium; its use in drinking water disinfection became more common in the 1950s (USEPA, 1999b). In the 1970s, more than 100 U.S. water treatment facilities used chlorine dioxide for taste and odor control, iron and manganese oxidation, or final disinfection; in Europe, chlorine dioxide was being used at several thousand water treatment facilities, primarily for final disinfection (Symons et al., 1977). In the 1980s, use of chlorine dioxide as an alternative primary disinfectant to chlorine increased in the United States after EPA promulgated a regulation for TTHM (Aieta and Berg, 1986). Since the late 1980s, chlorine dioxide has been evaluated (Dupuy et al., 2011; Loret et al., 2005; Jacangelo et al., 2002; Berg et al., 1988) and later implemented as an effective disinfectant to control *Legionella* and biofilm in hot and cold premise plumbing systems (Casini et al., 2014; Marchesi et al., 2013; Cristino et al., 2012; Marchesi et al., 2011; Zhang et al., 2009; Sidari et al., 2004).

Use of chlorine dioxide in PWSs is regulated by the Stage 1 and Stage 2 D/DBPRs. Chlorine dioxide itself can cause acute health effects and has an MRDL of 0.8 mg/L. Chlorite, a DBP of chlorine dioxide disinfection, is also regulated by EPA due to potential health concerns. The Stage 1 D/DBPR sets an MCL of 1.0 mg/L for chlorite.

Chlorine dioxide is usually generated on site from sodium chlorite solutions and one or more other chemical precursors (e.g., sodium hypochlorite, hydrochloric acid, sulfuric acid) or by an electrochemical oxidation process. Stock solutions produced on site typically have a concentration of 500 mg/L. Chlorine dioxide gas cannot be compressed or stored commercially because it is explosive under pressure. Therefore, chlorine dioxide gas is never shipped (USEPA, 1999b). Water treatment chemicals must meet the appropriate ANSI/AWWA standards or NSF/ANSI Standard 60 (GLUMRBSPPHEM, 2012).

2.3.3.2 Characterization of Effectiveness against *Legionella*

Laboratory and pilot-scale testing have generally shown that chlorine dioxide disinfection can be effective in controlling *Legionella*:

- Dupuy et al. (2011) compared chlorine dioxide, chlorine and monochloramine in treating *L. pneumophila* and *Acanthamoeba* strains alone or in co-cultures (i.e., *L. pneumophila* grown within amoebae). Dosage rates were 0.4 mg/L for chlorine dioxide, 2–3 mg/L for chlorine (for a residual free chlorine concentration of ~1 mg/L) and 0.8 mg/L for

monochloramine. All samples were treated with disinfectant for one hour and then the disinfectant residual was measured. Chlorine and chlorine dioxide were more efficient at reducing free *L. pneumophila* than co-cultured *L. pneumophila* (i.e., providing at least a 3-log (99.9-percent) reduction of the bacterial population at study conditions). Chlorine dioxide was found to be highly efficient in inactivation of *Acanthamoeba* M3 amoebae only, less so in inactivating the other two *Acanthamoeba* strains discussed in the paper.

- Loret et al. (2005) compared the performance of several alternative disinfectants under a controlled pilot-scale simulation of a typical premise plumbing system. Tap water and injection of cultured natural *Legionella* strains were used to establish biofilms in each pipe loop. Low temperature (35 degrees C, or 95 degrees F) and low water velocity were maintained to favor the growth of *Legionella* and biofilms. Each pipe loop was treated with one of the studied disinfectants for three months. The target dosage rate for chlorine dioxide was 0.5 mg/L. The authors determined that chlorine dioxide and chlorine were the most effective in controlling *Legionella*, biofilm and protozoa. Chlorine dioxide had longer residual activity in the system than did chlorine. Chlorite levels were measured in the chlorine dioxide pipe loop at levels >0.2 mg/L. *Legionella* populations decreased to undetected levels (<500 CFU/L) within the first three days of treatment for all disinfectants. Biofilm reduction started one week after treatment was initiated. Biofilm thickness was reduced to <5 µm with chlorine dioxide and several other disinfectants, as compared to a measured biofilm thickness of 13–35 µm in the untreated pipe loop.

- Jacangelo et al. (2002) conducted laboratory studies to evaluate chlorine dioxide, free chlorine and monochloramine for inactivation of waterborne emerging pathogens, including *Legionella*. The chlorine dioxide dose rate was 1.0 mg/L. Two different temperatures (5 and 25 degrees C, or 41 and 77 degrees F) and two different pH values (6.0 and 8.0) were examined. The observed CT values for 2-log (99-percent) reduction of *Legionella* were reported. At 5 degrees C, the observed CT values ranged from >320 to >1,000 min-mg/L at pH 6.0 and from >250 to 630 min-mg/L at pH 8.0. At 25 degrees C, the observed CT values ranged from 50 to 200 at pH 6.0 min-mg/L and from 50 to 130 min-mg/L at pH 8.0.

However, one laboratory study found that *L. pneumophila* was not inactivated by disinfection with chlorine dioxide at levels that might be used for shock disinfection (emergency remediation). Mustapha et al. (2015) compared culturability and viability of three *L. pneumophila* strains in response to chlorine dioxide exposure. At 4 mg/L, *L. pneumophila* could be detected using cell culture, but at 6 mg/L, no bacteria were detected. However, the authors found that VBNC cells could be detected at chlorine dioxide concentrations of 4–7 mg/L using flow cytometry. Two strains of the VBNC cells became culturable after co-culture with *Acanthamoeba polyphaga*, but neither strain was able to cause infection in macrophage-like cells.

Chlorine dioxide disinfection systems have been installed in hospitals to control *Legionella* and biofilm in hot and cold water systems (Casini et al., 2014; Marchesi et al., 2013; Cristino et al., 2012; Marchesi et al., 2011; Zhang et al., 2009; Sidari et al., 2004).

- Casini et al. (2014) reported the application of a WSP approach using multiple disinfectants and filtration to control *Legionella* in a hospital's hot water system. The risk management strategy was developed and refined over a 9-year period. Continuous disinfection with chlorine dioxide (0.4–0.6 mg/L in recirculation loops) was provided. Additional treatment included endpoint filtration and a shift to monochloramine disinfection (2–3 mg/L) after chlorine-tolerant *Legionella* spp. were identified. After nine years, the number of sampling sites that were positive for *Legionella* decreased by 51 percent, from 66.7 percent to 32.9 percent, and the mean *Legionella* count decreased by 78 percent.

- Marchesi et al. (2013) reported a strong reduction in *L. pneumophila* contamination in three hospital hot water systems over a three-year period compared to the untreated systems. A concentration of 0.50–0.70 mg/L chlorine dioxide was applied to the hot water systems, which contained water at temperatures up to 60 degrees C (140 degrees F) in the recirculation loop, with the goal of maintaining a minimum concentration of 0.30 mg/L at distal sites. On average, the three systems reduced *Legionella* occurrence from 96 percent of sampling sites to 46 percent.

- Cristino et al. (2012) described use of chlorine dioxide for chemical shock treatment and continuous treatment after the hot water system in a long-term care facility was found to be colonized with *L. pneumophila*. In addition to thermal shock and chemical shock with peracetic acid, chlorine dioxide was applied at a dose sufficient to obtain a 5-mg/L residual throughout the premise plumbing system for a one-hour contact time. The water was then drained and fresh water introduced to the systems until the chlorine dioxide residual was <0.3 mg/L. A continuous chlorine dioxide system was installed in the hot water supply at a dose sufficient to maintain a minimum 0.3-mg/L residual at distal taps. The shock treatment reduced *Legionella* counts from 10^4–10^5 CFU/L to zero to 10^2 CFU/L. Environmental monitoring conducted during the continuous chlorine dioxide treatment period showed that *Legionella* counts remained at stable levels (zero to 10^3 CFU/L). No cases of hospital-acquired legionellosis occurred during the study period.

- Marchesi et al. (2011) compared the performance of treatment alternatives for controlling *Legionella* contamination in hospital hot water systems, including two hot water plants that installed chlorine dioxide treatment systems in 2005. Chlorine dioxide successfully maintained *Legionella* levels at <100 CFU/L when the dosage rate was maintained at a minimum of 0.3 mg/L at outlets; however, when the boiler water temperature was less than 58 degrees C (136 degrees F), treatment was ineffective. Electric boilers and POU filters had better performance than chlorine dioxide.[5] The authors suggested implementing chlorine dioxide and electric boilers in parallel to control *Legionella*.

[5] The electric boilers were installed on cold water lines in high-risk areas; each boiler served one to two patient rooms.

- Zhang et al. (2009) evaluated using chlorine dioxide to treat for *L. pneumophila* in two hospitals reporting cases of hospital-acquired legionellosis. Water quality parameters were very similar between the two systems, except pH was 7.70 for Hospital A and 8.57 for Hospital B. Water temperatures in cold and hot water taps were 4–31 degrees C (39–88 degrees F) and 27–52 degrees C (81–186 degrees F), respectively. Hospital B had previously tried a superheat-and-flush of the hot water system and replacing a storage tank that was colonized with *Legionella*, but those measures were unsuccessful. Disinfection systems installed at Hospital A (January 2003) and Hospital B (April 2004) injected chlorine dioxide at the cold water service line to each building using a dosage rate of 0.5–0.7 mg/L. Although both hospitals achieved significant reductions in *Legionella* occurrence in the hot water system, Hospital B achieved control after six to 10 months of treatment, whereas Hospital A required 18 months. The longer treatment period for Hospital A was attributed to the longer time needed to achieve a chlorine dioxide residual >0.10 mg/L. The residual concentration for chlorine dioxide at the distal sites varied from zero to 0.11 mg/L depending on the building, date and type of tap (hot or cold). The occurrence of *Legionella* at hot water taps decreased from 60 percent of sampling sites before chlorine dioxide addition to ≤10 percent of sampling sites after treatment; however, a significant decrease in the concentration of *Legionella* in positive samples was not observed. No cases of hospital-acquired Legionnaires' disease were detected after installation of the chlorine dioxide system.

- Sidari et al. (2004) reported on the first controlled field evaluation in the United States of a chlorine dioxide treatment system installed in June 2000, at a hospital linked to three cases of hospital-acquired Legionnaires' disease. Legionellae were eliminated (i.e., the authors had no positive results) from the hot water system, but only after 20 months of treatment. Rates of positive *Legionella* detections decreased significantly, from 23 percent to 12 percent for hot water taps, and to almost zero percent for the cold water reservoir. Reductions in chlorine dioxide concentrations were observed at hot water distal sites and were attributed to a longer retention time and elevated water temperatures. Hot water temperatures at distal sites ranged from 26 to 61 degrees C (79 to 142 degrees F) during the second sampling phase. Average chlorine dioxide residuals were 88 percent lower for the hot water tap than the cold, or 0.08 mg/L and 0.68 mg/L, respectively. No cases of Legionnaires' disease occurred after the chlorine dioxide treatment system was installed.

2.3.3.3 Potential Water Quality Issues

Chlorite and chlorate are the most prominent byproducts of chlorine dioxide disinfection (WHO, 2011b; Gates et al., 2009; USEPA, 2006b). Chlorite could cause anemia in some people and affect the nervous systems of some infants, young children and fetuses of pregnant women. Ongoing exposure to chlorate ion can lead to an enlarged thyroid (USEPA, 2012). Findings on DBP formation in building water systems using chlorine dioxide disinfection include:

- In an Italian hospital where chlorine dioxide was used to control *L. pneumophila* in the hot water supply, chlorite levels higher than 0.7 mg/L were measured when the chlorine dioxide residual was > 0.3 mg/L (Marchesi et al., 2013).

- In another study (Zhang et al., 2009), chlorine dioxide concentrations among different sampling locations over two years ranged from zero to 0.70 mg/L, whereas chlorite concentrations ranged from zero to 0.82 mg/L. The average chlorate concentrations in hot and cold water were below the detection limit of 0.10 mg/L.

- Chlorine dioxide does not form the high levels of chlorinated DBPs that chlorination does (Gates et al., 2009).

- Compared to chlorine and monochloramine, chlorine dioxide has more objectionable tastes and odors at concentrations necessary for secondary disinfection (more than 0.2 mg/L in North America) (Gates et al., 2009). Although the odor threshold of chlorine dioxide in tap water is not well-documented in the literature, general practice indicates that concentrations from 0.2 to 0.4 mg/L are easily detected (Gates et al., 2009). Kerosene-like and cat-urine-like odors were reported in some homes with new carpets when volatizing chlorine dioxide reacted with airborne volatiles (Dietrich et al., 1991).

Chlorine dioxide is considered less corrosive than chlorine (Lin et al., 2011b). Some reports suggest that chlorine dioxide can cause damage to polyethylene pipes (Yu et al., 2013; Chord et al., 2011; Yu et al., 2011) while another study showed that no pipe failure occurred after 2,000 hours of exposure to 5 mg/L chlorine dioxide (Castagnetti et al., 2011). Chlorine dioxide concentrations tested by Yu et al. and Castagnetti et al. are greater than those likely to be used for continuous disinfection. High concentrations are a possibility for shock disinfection purposes. Information on other types of pipes is sparse (Gates et al., 2009). Loret et al. (2005) observed corrosion marks on mild and galvanized steel coupons installed in pipe loops for chlorine dioxide treatment that were similar to corrosion effects for other disinfectants (chlorine, chloramine, CSI and ozone), except that the coupons exposed to CSI also had copper deposits.

2.3.3.4 Operational Conditions

Parameter Conditions Indicating Operational Effectiveness

Dosage rate is an important design criterion for chlorine dioxide disinfection systems. Chlorine dioxide dosage rates of 0.4 to 0.7 mg/L were reported by systems experiencing successful treatment performance (HSE, 2014; Casini et al., 2014; Marchesi et al., 2013; Zhang et al., 2009). Zhang et al. (2009) reported that the dosage rate was between 0.5 and 0.7 mg/L, depending on the flow rate of cold water entering the buildings.

The required disinfectant dosage rate is dependent on system-specific conditions including pipe material and condition, the water's disinfectant demand, water temperature, the extent of biofilm on pipe surfaces, pipe diameter and length, complexity of the premise plumbing system, treatment goals (e.g., *Legionella* control) and the water turnover rate. Zhang et al. (2008) determined that scale from corroded iron pipe in the distribution system would cause more chlorine dioxide loss than typical levels of total organic carbon found in finished water. One study (Zhang et al., 2009) reported the chlorine dioxide demand of the premise plumbing was determined to be 0.20 mg/L after six hours of contact time at 23 degrees C (73.4 degrees F) and pH 7.8.

Maintaining a total chlorine dioxide residual of 0.1–0.5 mg/L at the tap is usually sufficient to control *Legionella*, although higher residuals may be necessary in a heavily colonized system (HSE, 2014). Some systems have established a treatment goal of maintaining a minimum chlorine dioxide residual of 0.3 mg/L at distal taps (Marchesi et al., 2013; Cristino et al., 2012; Sidari et al., 2004). If treatment with a residual higher than 0.8 mg/L is determined to be necessary, the facility should ensure that emergency disinfection procedures are developed and followed so that human consumption of a concentration of chlorine dioxide greater than the MRDL does not occur.

Several studies identified factors that limited the effective performance of chlorine dioxide disinfection for *Legionella* control:

- Casini et al. (2014) reported that performance of a hospital water system appeared to be affected by an accidental event in a water tank of the municipal water system that caused sediment buildup and increased water contamination in the hospital water system. After the event, no further reduction in *Legionella* colonization was observed with only disinfection treatment. As a result, the hospital modified its WSP to include POU filtration with 0.2-µm sterile filters in critical areas of the system (e.g., intensive care units (ICUs), transplant wards).

- The lack of proper monitoring for a chlorine dioxide treatment system for drinking water was noted at a New York health care facility after it experienced a *Legionella* outbreak in 2010 (CDC, 2013). Two hospitalizations for acute respiratory illness were reported and no deaths occurred.

- Zhang et al. (2009) noted the importance of achieving an adequate disinfectant residual and its effect on the amount of time needed to control *Legionella*.

- Sidari et al. (2004) reported differences in the time required to control *Legionella* in a hospital's hot and cold water systems after a chlorine dioxide treatment system was installed in June 2000. The water treatment goal was to achieve a minimum chlorine dioxide residual of 0.3 mg/L at distal sites. Chlorine dioxide residuals in the hot water loop averaged 0.08 mg/L (88 percent lower) compared to an average of 0.33 mg/L at cold water taps. This may explain why 20 months of treatment was required to control (i.e., achieve zero occurrence) *Legionella* from the hot water system, whereas only 15 months of treatment was needed for the cold water system.

Installation Considerations

The location of disinfectant application point(s) is a critical design decision. The location may affect the required dosage rate and the time needed to inactivate *Legionella*. For example, if chlorine dioxide is added at the cold water service entry point to the building, the dosage rate should be sufficient to achieve an adequate disinfectant residual at hot water taps at distant points in the building. However, the need to comply with drinking water standards may drive a design decision to install multiple treatment units in the building's premise plumbing system.

Monitoring Frequency and Location

The SWTR (USEPA, 1989a) requires that all PWSs using chlorine dioxide monitor for the presence of a disinfectant residual in the distribution system and at the EP. The disinfectant level must be at least 0.2 mg/L at the EP and detectable in at least 95 percent of samples collected within the distribution system. The Stage 1 D/DBPR requires that all PWSs using chlorine dioxide monitor daily at each entry point to the distribution system to ensure it is not exceeding the MRDL (USEPA, 1998). Chlorine dioxide is a contaminant with acute health effects. Chlorine dioxide has a short sample hold time and should be measured immediately after sample collection; therefore, under the Stage 1 D/DBPR, on-site analysis at the water system is required.

If the daily chlorine dioxide measurement exceeds 0.8 mg/L, three follow-up distribution system chlorine dioxide samples must be measured the following day, as required by the Stage 1 D/DBPR.

The Stage 1 D/DBPR and Stage 2 D/DBPR require that all PWSs using chlorine dioxide monitor chlorite for compliance with the MCL (USEPA, 2006b). Chlorite must be monitored daily at the EP, in addition to being measured in a three-sample set each month in the distribution system as detailed in the Code of Federal Regulations (CFR) at 40 CFR 141.132(b)(2). Daily monitoring can be conducted on-site; monthly monitoring should be conducted at a certified laboratory (see 40 CFR 141.131(b), Footnote 8 in Table).

Maintenance Needs

Operation and maintenance practices for chlorine dioxide disinfection systems include maintenance of a disinfectant residual, regular system cleaning and flushing, inspections and water quality monitoring. Routine flushing and water quality monitoring are recommended to assure that adequate disinfectant levels are maintained throughout the premise plumbing system (HSE, 2014).

2.3.4 Copper-Silver Ionization

2.3.4.1 Background

Commercially available CSI systems typically consist of flow cells that contain metal bars or anodes (containing copper and silver metals) surrounding a central chamber through which piped water flows. A direct electric current is passed between these anodes, releasing the copper and silver ions into the water stream. The amount of ions released depends on the composition of the anode and is controlled by the electrical current applied to the bars and the water flow rate.

The use of silver ionization for water disinfection was developed by the National Aeronautics and Space Administration (NASA) for 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 buildings with complex water systems to control the growth and occurrence of *Legionella* bacteria. Lin et al. (2011b) documented CSI applications controlling *Legionella* in hospitals worldwide.

2.3.4.2 Characterization of Effectiveness against *Legionella*

Case studies constitute the majority of the published reports on the efficacy of CSI in controlling *Legionella* in premise plumbing systems (Demirjian et al., 2015; Dziewulski et al., 2015; Chen et al., 2008; Mòdol et al., 2007; Blanc et al., 2005; Stout and Yu, 2003; Kusnetsov et al., 2001; Rohr et al., 1999; Liu et al., 1998; States et al., 1998; Liu et al., 1994). The studies generally describe situations where *Legionella* bacteria were found in a premise plumbing system and CSI was initiated in an attempt at *Legionella* control. Many of the reviewed laboratory studies indicate that copper and silver ions can inactivate *Legionella* and reduce the incidence of legionellosis. However, as with other technologies, other studies showed that *Legionella* can be protected from copper and silver ions when it is associated with biofilms or amoebae. The potential for *Legionella* to develop resistance to copper and silver ions has also been suggested by several studies.

- Dziewulski et al. (2015) demonstrated the efficacy of CSI for inactivating both *L. pneumophila* and *L. anisa* under alkaline water conditions (pH 8.7–9.9) in two health care facilities. No cases of legionellosis occurred during the study period. CSI treatment reduced the number of CFU and the percentage of samples found to be culture-positive. After CSI treatment was established, culture positivity was reduced from 70 percent to <30 percent. The study suggests that silver ions played a major role in controlling legionellae, generally in the range of 0.01-0.08 mg/L.

- Demirjian et al. (2015) characterized an outbreak at a Pennsylvania hospital between 2011 and 2012 and evaluated contributing factors in a large hospital using CSI to prevent *Legionella* growth. Of 25 locations where samples were collected for *Legionella* culture, 23 were positive for *Legionella*, while the mean copper and silver ion concentrations were measured at or above the manufacturer's recommended levels for *Legionella* control (0.30 and 0.02 ppm, respectively). They observed that *Legionella* remained viable *in vitro* in the presence of copper and silver ion concentrations within the manufacturer's recommended levels, while chlorine residual levels were low or not present during the investigation. They hypothesized that organic material could have increased during construction work in the hospital. The authors concluded that this could have led to consumption of the chlorine residual, leaving CSI as the only method for *Legionella* control.

- Chen et al. (2008) studied the implementation of copper-silver ionization in both hot and cold water at the point of entry to a hospital in Taiwan. CSI was applied to cold water because the subtropical climate in Taiwan resulted in cold water with temperatures up to 30 degrees C (86 degrees F). During the first three months of implementation, copper/silver concentrations in the hospital wards were 0.094/0.020, 0.114/0.014 and 0.110/0.007 mg/L at months 1, 2 and 3, respectively. The percentage of positive *L. pneumophila* samples declined from 30 to 20 percent. During months 4–7, the hospital increased the copper/silver levels to 0.143/0.008, 0.157/0.011, 0.180/0.017 and 0.212/0.014 mg/L, respectively. The percentage of positive samples declined to 5 percent and, in months 7–11, to zero. In the ICUs, however, the hospital was able to reduce but not completely control *Legionella* during the study. Copper and silver levels in the ICUs

were thought to be diluted by connection with a reverse osmosis system installed in the unit.

- Mòdol et al. (2007) described how a large hospital experienced success in decreasing the number of positive *Legionella* samples after initiating CSI. The hospital had discontinued the use of chlorine in the hot water system due to difficulties in maintaining minimum concentrations at distal points in the building's premise plumbing system. It also discontinued frequent superheating due to pipe damage and poor compliance with heating and flushing procedures. Initially, the copper and silver levels were maintained at 0.1–0.3 mg/L and 0.01–0.03 mg/L, respectively. While the treatment system was under repair for two months, the percentage of positive samples for *Legionella* increased from 20 percent to 65 percent. Following the interruption in treatment, hospital staff increased copper and silver concentrations to 0.4 and 0.04 mg/L. *Legionella* samples taken after the increase were 16 percent positive.

- Blanc et al. (2005) reported that no significant difference was observed in the percentage of water and biofilm samples positive for *Legionella* spp. after CSI treatment was installed in 1999. The CSI system electrodes were composed of 8 percent silver and 92 percent copper, and the copper concentration in the water was 0.3 mg/L. A significant reduction in *Legionella* isolates was observed after the hot water system temperature was increased from 50 to 65 degrees C (122 to 149 degrees F) in the year 2000.

- Survey results by Stout and Yu (2003) showed that of 13 hospitals reporting at least 30 percent *Legionella*-positive samples before CSI treatment began, nine hospitals reported a sustainable (over a period of 6–9 years) decrease in the number of *Legionella*-positive samples; five hospitals reported no positive samples after treatment. This survey also showed that all of the hospitals reported cases of hospital-associated Legionnaires' disease before CSI treatment, and all but one reported no cases after treatment.

- Lin et al. (2002) studied the effects of pH and other water quality parameters on CSI treatment for *Legionella* control using water from a hospital hot water system. At pHs of 7.0 and 9.0, copper ions achieved a 6-log and 1-log (99.9999 and 90 percent) reduction, respectively, in the number of *L. pneumophila* in 24 hours. Silver ions achieved a 6-log reduction in 24 hours at all ranges of water quality parameters tested.

- Based on four years of monitoring data, Kusnetsov et al. (2001) reported that legionellae were no longer detected in the circulating warm water of a hospital water system after CSI treatment was employed and silver concentrations were increased to levels greater than 3 µg/L. However, water samples collected from taps and showers that were not used on a regular basis showed that even a high silver concentration (55 µg/L) did not prevent growth of *Legionella*.

- Rohr et al. (1999) indicated that CSI had an initial impact on *Legionella* occurrence in the hot water system of a German university hospital, where 100 percent of sampling sites were positive for *Legionella* before treatment and 55 percent of sampling sites had positive results one year after treatment was initiated. Over the next three years, 75–78

percent of samples were positive for *Legionella*. However, Lin (2000) disagreed with Rohr et al.'s (1999) results that the CSI system did not effectively control *Legionella* in this system. Lin (2000) pointed out that the CSI system was not effective because it did not maintain an adequate concentration of copper and silver ions in the treated premise plumbing system (200–400 µg /L of copper and 20–40 µg /L of silver was crucial). Lin (2000) also noted that Rohr et al. did not provide evidence for the development of *Legionella* resistance to copper or silver. Rohr (2000) responded to Lin's (2000) comments, and explained that the purpose of the study was to evaluate control of *Legionella* using a CSI system that met German regulations limiting silver ion concentrations to a maximum of 10 µg/L.

- States et al. (1998) reported that CSI treatment was successful in reducing the percentage of samples testing positive for *Legionella* from 100 percent to less than 17 percent on average over a two-year period.

- Lin et al. (1996) found that *L. pneumophila* serogroup 1 was completely inactivated (6-log (99.9999-percent) reduction) within 2.5 hours using copper ions at concentrations of 0.1 mg/L without silver ions, and more than 24 hours was needed to achieve a similar reduction using silver ions at concentrations up to 0.08 mg/L without copper ions. When both copper and silver ions were used, inactivation was achieved at copper and silver concentrations of 0.04 mg/L.

- Based on laboratory studies with filtered well water (pH 7.3), Landeen et al. (1989) determined that copper ions (at 0.4 mg/L) and silver ions (at 0.04 mg/L) can achieve a 3-log (99.9-percent) reduction in *L. pneumophila* at room temperature when the contact time is at least 24 hours.

Other studies have reported the potential occurrence of *Legionella* strains that appear to be less sensitive to the toxic effects of certain chemicals such as copper and silver. Microorganisms are highly adaptive. It is well documented that within the bacterial world there are cellular mechanisms which allow bacteria to survive hostile environments.

There is an understanding of how bacterial gene systems can confer resistance to copper and silver (Nies, 1999). Some of these gene systems are found in *Legionella* (Bondarczuk and Piotrowska-Seget, 2013). One common resistance mechanism in gram-negative bacteria (such as *Legionella*) requires an energy-dependent protein that protects the cell by acting as a pump to export copper ions out of the cell (Bondarczuk and Piotrowska-Seget, 2013). The occurrence of *Legionella* strains potentially tolerant of silver in CSI treatment was noted by Rohr et al. (1999); however, Lin (2000) commented that Rohr et al.'s (1999) conclusion is not supported by any data in their report and noted the silver ion levels used were below the recommended levels for control of *Legionella*. Rohr (2000) responded to Lin (2000) that the multiple regression analysis reported in the 1999 paper shows a decreasing influence of silver ions on *Legionella* counts during the 4-year study period.

Hypochlorous acid, the active disinfecting chlorine species, is in part toxic to bacterial cells by virtue of interfering with the production of energy (in the form of adenosine triphosphate (ATP)) needed for many cellular processes including heavy metal resistance enzymes (Barrette et al.,

1989). The synergy between free chlorine and heavy metal ions on *Legionella* copper resistance mechanisms and *Legionella* susceptibility is generally unstudied. However, Landeen et al. (1989) showed increased (although not statistically significant) inactivation rates of *L. pneumophila* with copper and silver ions in the presence of 0.4 mg/L free chlorine.

2.3.4.3 Potential Water Quality Issues

Use of CSI may result in corrosion. Materials compatibility and water quality will dictate the severity of corrosion. Awareness of the types of materials and water chemistry in a premise plumbing system is critical to maintaining system integrity. Loret et al. (2005) observed corrosion marks on mild and galvanized steel coupons installed in pipe loops for CSI treatment that were similar to corrosion effects for other disinfectants (chlorine, chloramine, chlorine dioxide and ozone), except that the coupons exposed to CSI also had copper deposits. Although pitting corrosion was not observed during the study, intense corrosion occurred within the pipe loop after the study was completed, suggesting that CSI treatment may lead to pipe corrosion under some conditions. Type III pitting usually occurs in soft water with alkaline pH >8.0 (Edwards et al., 1994), at distal or stagnant locations and at moderately warm temperatures Edwards et al., 1994). Lytle and Schock (2008) found that waters with high pH (pH 9 and possibly as low as 8), low dissolved inorganic carbon (<10 mg/L and possibly as high as 25 mg/L) and chloride levels of 14–38 mg/L promoted pitting corrosion.

High concentrations of both copper and silver have been reported in systems employing CSI, to levels approaching the maximum contaminant level goal and action level for copper (1.3 mg/L) and the secondary maximum contaminant level (SMCL) for silver (0.1 mg/L) (States at al., 1998; Rohr et al., 1999). As copper levels in copper piping can rise during periods of stagnation, high levels of copper can occur in early morning first-draw water samples (Araya et al., 2004; Araya et al., 2003a; Araya et al., 2003b; Araya et al., 2003c; Araya et al., 2001; Knobeloch et al., 1994). Copper, but not silver, was found to concentrate on biofilm material in premise plumbing systems employing CSI treatment (Liu et al., 1998; Zevenhuizen et al., 1979).

Copper toxicity from ingestion of drinking water has been reported even without the contribution of copper from CSI systems (Araya et al., 2004; Araya et al., 2003a; Araya et al., 2003b; Araya et al., 2001; Knobeloch et al., 1998; Knobeloch et al., 1994). Symptoms of copper toxicity include nausea, abdominal cramps, vomiting and diarrhea.

Both copper and silver can have negative aesthetic effects on water: color, taste and odor and staining issues (Hong et al., 2010; Dietrich, 2009; Stout and Yu, 2003; Edwards et al., 2000; Knobeloch et al., 1998; Knobeloch et al., 1994). Edwards et al. (2000) attributed the rare occurrence of blue water to corrosion of copper plumbing. Ingesting high levels of silver can also lead to a skin discoloration condition called “argyria” (Drake and Hazelwood, 2005; WHO, 2003; USEPA, 1989b). According to WHO (2003), the lowest dose of silver that may lead to occurrence of argyria has not been determined, but, in general, silver levels up to 0.1 mg/L can be tolerated without risk to health. Silver levels approaching the SMCL of 0.1 mg/L have been reported in premise plumbing systems using CSI treatment (Rohr et al., 1999; States et al., 1998).

Laboratory studies have been conducted on the effectiveness of CSI in reducing levels of other bacterial species commonly found in built environments, including *Pseudomonas, Stenotrophomonas, Acinetobacter* (all gram-negative bacteria like *Legionella*) and *Mycobacterium*. Copper and silver ions appear to act synergistically (the total effect is greater

than the sum of the individual effects) toward *L. pneumophila* (Lin et al., 1996), *Pseudomonas* and *Acinetobacter* (Huang et al., 2008), while the ions act antagonistically (the interaction of the two metals lessens the effect of each metal acting individually) toward *Stenotrophomonas* (Huang et al., 2008). *Mycobacterium* was shown to be 100-fold less sensitive to copper and silver ions than *Legionella* (Lin et al., 1998b), and copper and silver levels that controlled *Legionella* were unable to control the occurrence of *Mycobacterium* in a hospital premise plumbing system (Kusnetsov et al., 2001). Shih and Lin (2010) tested CSI in a model water system against *Pseudomonas*, *Stenotrophomonas* and *Acinetobacter* with 72 hours exposure to copper and silver concentrations of 0.2 and 0.02, 0.4 and 0.04, and 0.8 and 0.08 mg/L. In biofilm, CSI achieved 2- to 3-log reduction (99-to 99.9-percent) of these pathogens. In free-floating bacteria, CSI achieved a 4- to 7-log reduction, except for *Acinetobacter*, where even with 0.8 and 0.08 mg/L copper and silver concentrations, the reduction was only 2 log (99 percent). The authors noted that concentrations of copper and silver decreased during the 72 hours, probably because ions were attached to individual cells, and that this could have contributed to regrowth during that period.

Field studies of CSI have reported some effectiveness in reducing fungi in hospital water systems, especially *Fusarium* spp. (Chen et al., 2013). A report on healthcare facilities in Spain with (n=9) and without (n=7) ionization treatment systems cited a fungal isolation rate of 28 percent versus 77 percent, respectively (Pedro-Botet et al., 2007). CSI has not been reported to reduce levels of heterotrophic bacteria or amoebae in either a controlled laboratory study (Rohr et al., 2000) or a case study (States et al., 1998).

2.3.4.4 Operational Conditions

Parameter Conditions Indicating Operational Effectiveness

Maintaining copper and silver at the levels recommended by the manufacturer is a best practice in achieving operation effectiveness. Note that monitoring typically includes measurement of the total metal concentration, which includes copper and silver that are bound up as complexes, as well as copper and silver ions. The presence of copper and silver ions is thought to be critical for treatment effectiveness, so maintaining proper pH and avoiding interfering materials (e.g., phosphates, chlorides) is also important (Zevenhuizen et al., 1979). Examples of interferences include:

- In the presence of 20–40 mg/L of chloride ions, silver ion levels are significantly (60 percent) decreased by complexing with chloride (and are presumably less microbiocidal) (Lin et al., 2002).

- Phosphates, such as those added for corrosion control, can bind to copper ions as well as silver ions, reducing their treatment effectiveness (Zevenhuizen et al., 1979).

The presence of dissolved organic carbon at 2 mg/L, calcium at 100 mg/L, magnesium at 80 mg/L and bicarbonate at 150 mg/L did not appear to decrease the treatment efficacy of copper and silver ions against *L. pneumophila* in a laboratory study (Lin et al., 2002).

The impact of pH on the ionic nature (and thus the microbiocidal action) of copper in solution is also important. At pH levels >6.0, copper forms insoluble complexes with a number of compounds. While in the pH range typical of potable waters (pH 6–9), silver ions are not

diminished. In a controlled laboratory study (Lin et al., 2002) found that at a pH of 7, exposure to 0.4 mg/L of copper resulted in a 4-log (99.99-percent) reduction of *L. pneumophila* in one hour however, at a pH of 9, there was no appreciable decrease in *L. pneumophila* over the same period of time with the same copper exposure. Dziewulski et al. (2015) demonstrated efficacy of CSI under alkaline water conditions (pH 8.0-9.8) and found that silver ions controlled the *L. pneumophila* serotypes 1 and 6, and *L. anisa*.

With regard to the effects of temperature, one study (Landeen et al., 1989) found no significant difference in *L. pneumophila* inactivation rates in experiments conducted at room temperature (21–23 degrees C, or 69.8–73.4 degrees F) and elevated temperature (39–40 degrees C, or 102.2–104 degrees F) using water with 0.2 mg/L free chlorine, with or without 400 µg/L of copper and 40 µg/L of silver.

Installation Considerations

CSI systems can be plumbed into either the cold water entry pipe or plumbed into the hot water line. Care should be taken to install devices downstream of any process that will remove or exchange copper and silver ions. Note that construction that includes new copper pipe can add copper to water for a time via leaching.

Newly installed CSI systems generally require a period of time to adjust system output in order to achieve the desired level of metal ions. Representatives from the manufacturer are typically involved in on-site start-up and balancing of the system.

Monitoring Frequency and Location

Initial monitoring during start-up is critical to ensure the copper action level in the Lead and Copper Rule is not exceeded. A facility that is considering installation of CSI should consult with its primacy agency to determine a protocol for initial monitoring. During the initiation of CSI, weekly monitoring with inductively coupled plasma/mass spectrometry (ICP/MS) (e.g., EPA Method 200.8) or atomic absorption spectroscopy (e.g., Standard Methods 3111B) can be conducted to determine accurate levels of copper and silver.[6] As treatment proceeds, the frequency of analysis may be reduced, but these methods remain the only reliable and accurate means to determine copper and silver concentrations.

Lin et al. (2011b) recommend monitoring copper on a weekly basis using a field colorimeter kit, and monitoring silver once every two months by atomic absorption spectroscopy or the inductively coupled plasma method. Operational monitoring of copper is generally conducted at various locations throughout the premise plumbing system to monitor for process changes in copper concentration (e.g., high copper concentrations that may be indicative of improper application, and no detectable copper). Based on a 1995 survey of 16 hospitals, Stout and Yu

[6] The National Environmental Methods Index (https://www.nemi.gov/home/) "is a searchable database that allows scientists and managers to find and compare analytical and field methods for all phases of environmental monitoring."

(2003) reported that 94 percent (15 of 16) of hospitals conducted routine monitoring for copper and silver ions.

According to the United Kingdom Health and Safety Executive (2014), both copper and silver levels should be monitored monthly, or no less than quarterly, at the same locations within the building, using appropriate sampling procedures, and submitted for analysis by ICP/MS or atomic absorption (HSE, 2014). Sampling locations will vary in specific buildings and should include both taps that are frequently and infrequently used. When appropriate, the facility owner or operator should work with the primacy agency to determine a site sampling plan for the water system. First-draw and flushed samples will often yield different results (Liu et al., 1994). First-draw sample testing can indicate how periods of low water flow may affect metal levels given the water quality conditions found in a specific building, while flush samples will measure the metal levels in the main cold or hot water lines feeding individual taps. Knowledge of how water flows in any particular building is essential in determining the best monitoring frequency and locations.

Maintenance Needs

The copper- and silver-containing anodes are sacrificial and should be rehabilitated periodically as they become smaller, according to the recommendations of the manufacturer. Anodes can also wear down due to high shear velocities (Chen et al., 2008). The anodes typically will develop scale from calcium in all but the softest waters and should be cleaned by scraping/acid treatment on a regular basis. Scale build-up reduces the surface area from which ions can be released, lowering the ion output. Any time a component of a water system is opened to the environment for maintenance, such as scraping, procedures should ensure that the system components are re-installed in a sanitary condition (i.e., disinfected).

Regular flushing of water lines (either through the frequent use of taps or routine weekly flushing) was cited as a critical factor in maintaining the effectiveness of CSI systems (Kusnetsov et al., 2001; Liu et al., 1994).

2.3.5 Ultraviolet Light Disinfection

2.3.5.1 Background

UV disinfection is a well-established treatment technology for inactivating pathogens present in the environment. In the drinking water context, UV disinfection was initially most widely used in Europe, with hundreds of installations in place by 1985 (USEPA, 2006c). In North America, UV disinfection has been more widely employed in drinking water applications since 2000 to address health concerns associated with *Cryptosporidium*. As of the spring of 2008, there were at least 300 PWSs in the United States and Canada with UV installations treating flows >350 gallons per minute (Wright et al., 2012).

UV reactor validation is used to define the operational conditions under which the pathogens of concern are inactivated for a specific UV reactor manufacturer and model. Validation is a method of determining the operating conditions under which a UV reactor delivers a specified dose. This generally involves initial tests using a surrogate organism (e.g., bacteriophage MS2) rather than the target pathogen (e.g., *Cryptosporidium*) to establish the dose relationship between the two organisms. The conditions that are examined for full-scale testing to establish dose are

flow rate, UV transmittance (UVT) (a measure of the fraction of incident light transmitted through a material) and lamp output. EPA has developed guidance for validation of UV reactors (USEPA, 2006c). There are also validation standards for UV reactors from organizations based in Austria (Österreichisches Normungsinstitut – ÖNORM) and Germany (Deutsche Vereinigung des Gas- und Wasserfaches – DVGW) that use a benchmark UV dose of 40 millijoules per square centimeter (mJ/cm^2) (GLUMRBSPPHEM, 2012; USEPA, 2006c).

There are two methods for validating UV units. In short, the setpoint approach establishes a measured UV intensity that corresponds to a specific dose and flow rate. The dose control method (also referred to as the calculated dose approach) provides a means of determining the required intensity that corresponds to a specific flow rate, UVT and dose. Reactors using the setpoint approach do not need a separate UVT monitor and in some cases may be easier to operate; however there are operational disadvantages (USEPA, 2006c).

2.3.5.2 Characterization of Effectiveness against *Legionella*

There are several important lessons from installations of UV disinfection in hospital settings and UV installations in general:

- UV disinfection can be effective at controlling *Legionella* in facility piping (Hall et al., 2003; Franzin et al., 2002; Liu et al., 1995). In the case of one new facility, a UV disinfection unit was installed on the incoming water supply, and none of the 930 cultures of hospital water were positive. In addition, there were no confirmed hospital-acquired *Legionella* infections over a 13-year study period (Hall et al., 2003).

- UV is only effective at inactivating *Legionella* in the water that flows through the UV reactor. For existing facilities with *Legionella* present in the piping systems downstream of a UV reactor, supplemental controls such as thermal treatment or chemical disinfection will be necessary.

- UV reactors need to be maintained to remain effective. The quartz sleeves that house the reactors can be fouled by iron, manganese, calcium carbonate or other deposits that decrease UV output. Lamps and other reactor components also need to be replaced periodically in order to maintain treatment effectiveness. Fouling of the UV lamps was found to decrease effectiveness of the UV treatment. Liu et al. (1995) added filters to prevent scaling on UV lamps installed near the point of use in a hospital's cold and hot water systems. After treatment with superheat/flush and shock chlorination, and installation of filters to remove particles that foul the UV lamps, the UV intensity of the lamps remained at 100 percent throughout the experiment and the showers remained *Legionella*-free for a period of three months.

Relatively low UV doses appear to inactivate *L. pneumophila* (Exhibit 2-1). A dose of 1 mJ/cm^2 was found adequate, in a recirculating model system, to achieve 99-percent (2-log) reduction in six different *Legionella* species. (Gilpin et al., 1985).

A dose of 30 mJ/cm^2 achieved 99.999-percent (5-log) reduction in 20 minutes in a recirculating model premise plumbing system under three different test conditions (non-turbid water at 25 degrees C (77 degrees F); turbid water at 25 degrees C; and non-turbid water at 43 degrees C

(109.4 degrees F)). However, viable numbers of *L. pneumophila* remained in the treated water despite six hours of continuous UV light exposure. UV irradiation was not affected by turbid conditions or increased temperature. (Muraca et al., 1987).

Usually, there are limited opportunities for exposure to light for water treated and held in premise plumbing systems. However, if there is a significant opportunity for light repair (repair of UV-induced DNA damage using photo-reactivating light), such as in water used in tubs, pools and baths, a higher UV dose should be considered. At a UV dose adequate to achieve 99.9-percent (3-log) reduction of *L. pneumophila*, subsequent exposure to fluorescent light for one hour resulted in only a 68 percent (0.5-log) reduction following initial inactivation by low pressure (LP) UV lamps and only 60 percent (0.4-log) reduction following inactivation by medium pressure (MP) UV lamps (Oguma et al., 2004). Similar significant light repair of *Legionella* has been observed by others (Knudson, 1985).

Exhibit 2-1: UV doses (mJ/cm^2) for inactivation of *L. pneumophila*

***L. pneumophila* strain**	**Lamp Type**	**1-log**	**2-log**	**3-log**	**4-log**	**Reference**
Philadelphia Type 2	LP	0.92	1.84	2.76	No data	Antopol and Ellner, 1979
Philadelphia 1 (no light repair)	LP	0.5	1.0	1.6	No data	Knudson, 1985
Philadelphia 1 (with light repair)	LP	2.3	3.5	4.6	No data	Knudson, 1985
Philadelphia 1 ATCC33152	LP	1.6	3.2	4.8	6.5	Oguma et al., 2004
Philadelphia 1 ATCC33152	MP	1.9	3.8	5.8	7.7	Oguma et al., 2004

Notes:
LP = Low pressure lamps, which have a single output of UV peaking around a wavelength of 254 nanometers.
MP = Medium pressure lamps, which have polychromatic (or broad spectrum) output of UV at multiple wavelengths.

2.3.5.3 Potential Water Quality Issues

UV disinfection does not produce a disinfectant residual (USEPA, 2007). Also, when UV disinfection is applied to waters containing a disinfectant residual, the residual may be diminished following treatment with UV (USEPA, 2006c). Therefore, water treated using only UV disinfection may, in some cases, be susceptible to contamination at downstream points. More than one type of disinfection or other control measure may be needed to protect the treated water downstream of UV disinfection, between the UV lamp and the taps and other water outlets (e.g., showerheads).

At UV doses typically used in drinking water, UV disinfection does not support the formation of regulated DBPs (USEPA, 2006c). In addition, UV disinfection does not change the pH or treated water quality in such a way as to make it more corrosive to premise plumbing (USEPA, 2006c).

Mercury can be released into the treated water when a UV lamp breaks (Wright et al., 2012). The amount of mercury that could potentially enter the water depends on the type of lamp and operation. Vapor phase mercury can dissolve into solution and be discharged downstream

whereas liquid phase or amalgam mercury would tend to settle in the UV reactor. The author recommends developing a mercury mitigation plan (Wright et al., 2012).

2.3.5.4 Operational Conditions

Parameter Conditions Indicating Operational Effectiveness

Water quality data are needed to adequately characterize the water to be treated by a UV reactor and identify any pre-treatment or UV equipment design features that may be necessary. Manufacturers may have their own data requests, though the following list will cover most water quality information needed (AWWA, 2012; USEPA, 2006c):

- Temperature – Some reactor components may not be tolerant of water >35 degrees C (95 degrees F). For this reason, the UV manufacturer should be consulted about the thermal tolerances of the equipment for installations on hot water plumbing.

- Turbidity – Excessive turbidity and certain dissolved species inhibit the effectiveness of UV disinfection (WHO, 2011). Light transmission through water is impaired by particulates.

- Disinfectant type and residual – Some reactor components may not be tolerant of certain disinfectants or high doses, so UV equipment manufacturers should be consulted about exposure of UV reactors to chemical disinfectants.

- UVT – Components in the water can absorb UV light and reduce the dose delivered to the microorganisms from the UV reactor. UVT (which can be calculated from UV absorbance) is a key parameter in making sure that the UV reactor is properly sized for the facility.

- Iron and manganese – These constituents can foul quartz sleeves, leading to decreased UV output. Iron concentrations >0.1 mg/L may cause operational issues.

The operation of a small UV reactor is typically governed by two key parameters: the flow through the reactor and UV sensor reading(s). Over time, UV sensors will drift out of calibration. For this reason, the readings from a UV duty sensor installed in the reactor should be compared against a reference sensor temporarily inserted in the reactor. PWSs typically make these sensor checks on a monthly basis. If the calibration ratio between the duty and reference sensor readings is >1.2, then follow-up actions such as recalibration or replacement of the UV sensor should be taken (USEPA, 2006c). For installations that use an online UVT monitor to control UV output, weekly comparisons between online and benchtop UVT measurements are recommended (USEPA, 2006c).

Installation Considerations

There are several sources of design guidance for the application of UV disinfection to potable water supplies (AWWA, 2012; USEPA, 2006c). These references cover a range of applications from those producing only a few gallons per day to millions of gallons per day. The following checklist is tailored to institutional settings for *Legionella* control:

- Hydraulics should allow for even flow through the reactor. Control valves and reducers should be avoided within five pipe diameters upstream of the UV reactor. Pipe expansions should also be avoided for at least ten pipe diameters upstream of the reactor to avoid jetting and swirling flow through the UV reactor.

- Redundancy or other measures should be built in to allow a UV reactor to be taken out of service for cleaning, lamp replacement and other maintenance.

- Valves to isolate UV reactors may be necessary. In some cases, such as when UV reactors are flooded with cleaning chemicals, special valve arrangements may be beneficial on the outlet and inlet piping.

- Power quality analysis includes review of sub-second power interruptions and voltage sags at the location of a proposed UV installation. Power protection, power conditioning equipment or an uninterruptible power supply may be necessary in some cases.

- Alarm and reactor shutdown conditions should be clearly identified.

- A lamp breakage response plan should be developed that defines emergency response actions that will be taken if a lamp breaks. Low velocity traps or other piping configurations to collect broken lamp components should be considered. The potential for hydraulic transients should be evaluated because they may cause the quartz sleeves that house UV lamps to fail.

Maintenance Needs

UV reactors, like other *Legionella* treatment options, require routine maintenance to ensure that the UV dose remains adequate for inactivation of pathogens. Some of the basic maintenance items include cleaning the quartz sleeves housing the lamps and periodically replacing the lamps, as their output decreases with time. Most UV lamps installed in smaller reactors will typically be rated for 8,000–12,000 hours of operation (one year of continuous operation equals 8,736 hours). To better understand the lamp output over time, premise plumbing operators may want to consult with the UV equipment manufacturer (USEPA, 2006c). In addition, some reactor components can be affected by disinfectants, including chlorine, added prior to the reactor, requiring additional maintenance. For a detailed list of recommended maintenance activities for a UV reactor, please see EPA's Ultraviolet Disinfection Guidance Manual for the Final Long Term 2 Enhanced Surface Water Treatment Rule (USEPA, 2006c).

2.3.6 Ozone

2.3.6.1 Background

Ozone is used in drinking water treatment for disinfection and oxidation (USEPA, 1999d, 2007). It is generated on-site as a gas using either air or liquid oxygen and is then transferred (dissolved) into the water phase. When dissolved in water, molecular ozone (O_3) is unstable and decomposes to hydroxyl radical, which is a stronger and typically more reactive oxidizing agent than molecular ozone. Ozone decomposes quickly during water treatment (USEPA, 1999d, 2007). Therefore, during a typical ozonation process, both molecular ozone and the hydroxyl radical

may contribute to the oxidation of contaminants of concern. The relative importance of these two oxidants depends on the concentrations of the oxidants and the reactivity of the contaminant with each oxidant.

The use of ozone in drinking water treatment is widespread throughout the world (Steiner et al., 2010). As an oxidant, ozone can be used to oxidize iron, manganese, taste and odor compounds, and DBP precursors. It can oxidize organic matter into smaller molecules that are more easily biodegradable. As a primary disinfectant, ozone is more effective than chlorine, chloramines and chlorine dioxide for inactivation of *Cryptosporidium*, *Giardia* and viruses (USEPA, 1999d, 2007). However, ozone cannot be used as a secondary disinfectant because it decays very rapidly and cannot maintain a residual in the distribution system (USEPA, 1999d, 2007).

2.3.6.2 Characterization of Effectiveness against *Legionella*

Information on ozone systems installed in hospitals and other types of buildings for *L. pneumophila* control is lacking. Only one paper, by Edelstein et al. (1982), evaluated the efficacy of ozone for eradicating *L. pneumophila* in hospital plumbing fixtures, but the result of the study was inconclusive.

Edelstein et al. (1982) applied continuous ozonation to the water supply in an unoccupied hospital building to evaluate whether it would control *L. pneumophila* in plumbing fixtures with positive cultures. The water supply was split into two wings: one treated with ozone, the other untreated. In their laboratory study, using distilled water, more than 3-log (99.9-percent) reduction in *L. pneumophila* was achieved by exposure to 0.32 mg/L of ozone for 20 minutes. However, results from ozonation of the water supply system (average ozone levels of 0.79 and 0.58 mg/L in two study phases, respectively) were difficult to interpret because the non-ozonated water in the control wing also showed inactivation of *L. pneumophila* due to a higher water usage rate and an unexpected rise in the chlorine residual in the control wing (average chlorine residual levels of 0.24 and 0.12 mg/L in two study phases, respectively). Although the treatment wing had a smaller number of positive cultures (3 of 12) than the control wing (8 of 12), the researchers could not reach a conclusion on the role of ozone in the inactivation of *L. pneumophila*. The study indicated that when ozonation was stopped, *L. pneumophila* regrew and reached levels close to the pre-test conditions at the end of the stagnation phase. Moreover, the authors pointed out one important factor for continual dosing of ozone, namely that residual ozone at the faucet or shower head led to the release of gaseous ozone into the air (an issue discussed in Section 2.3.6.4).

Several laboratory studies have reported rapid and effective inactivation of *Legionella* with ozone (Jacangelo et al., 2002; Domingue et al., 1988; Muraca et al., 1987).

- Loret et al. (2005) used a simulated distribution system consisting of pipe loops to compare the effectiveness of several disinfectants to control Legionella in biofilms in premise plumbing. The study concluded that ozone was effective to control planktonic and biofilm-associated populations within the pipe loops but was ineffective within dead end sections. For a more detailed description of the Loret (2005) study see Section 2.3.1.2.

- Jacangelo et al. (2002) conducted laboratory studies to evaluate multiple disinfectants, including ozone, for inactivation of waterborne emerging pathogens including *Legionella*. The ozone dosage rate was 1.0 mg/L. The model-predicted CT values for 2-log (99-percent) inactivation of *Legionella* at pH 7 were 2.5, 0.16 and 1.1 min-mg/L at 5, 15 and 25 degrees C (41, 59 and 77 degrees F), respectively.

- Domingue et al. (1988) conducted laboratory experiments to compare the bactericidal effects of ozone, hydrogen peroxide and free chlorine on "free" *L. pneumophila* cells. Ozone was the most potent of the three disinfectants, with a greater than 2-log (99-percent) inactivation in *L. pneumophila* occurring during a 5-minute exposure to 0.10–0.3 mg/L ozone. The researchers reported little to no effect of pH and temperature on ozone inactivation of *L. pneumophila.* The pH ranged from 7.2 to 8.9. Experiments were conducted at 25, 35 and 45 degrees C (77, 95 and 113 degrees F).

- Muraca et al. (1987) compared the efficacy of chlorine, heat, ozone and UV light for inactivating *L. pneumophila* in a bench-scale model plumbing system. *L. pneumophila* was added to the system and allowed to circulate. Continuous ozonation for five hours at a concentration of 1 to 2 mg/L achieved a 5-log inactivation of *L. pneumophila* at 25 and 43 degrees C (77 and 109.4 degree F, respectively). Neither turbidity nor the higher temperature (43 degrees C, or 109.4 degrees F) was reported to affect the efficacy of ozone.

2.3.6.3 Potential Water Quality Issues

Ozone decomposes in water relatively rapidly. The half-life of ozone in finished drinking water depends on temperature, pH and alkalinity, and can vary from minutes to hours. This time-scale is short relative to chlorine-based disinfectants, and as such, ozone is not generally considered to produce a disinfectant residual. Therefore, water treated with ozone may, in some cases, be susceptible to contamination at downstream points. For this reason, more than one type of treatment or control measure may be necessary to protect the treated water.

Disinfection byproducts formed from ozone disinfection include bromoform, monobromoacetic acid, dibromoacetic acid, dibromoacetone, cyanogen bromide, chlorate, iodate, bromate, hydrogen peroxide, hypobromous acid, epoxides, ozonates, aldehydes, ketoacids, ketones and carboxylic acids (WHO, 2011b).

Ozonation of water containing inorganic bromide can produce bromate, a regulated DBP with an MCL of 10 µg/L. The disinfection process of a PWS will likely have transformed any bromide in water to organically bound bromine or inorganic bromamines. In either case, these forms of bromine are less likely to contribute to bromate formation via an ozonation process in a premise plumbing system. As such, bromate formation may not be as relevant as in the water treatment plant.

Other ozonation byproducts such as aldehydes and organic acids are more readily biodegradable and may contribute to assimilable organic carbon (AOC) and hence biological growth in the distribution system. In addition, these ozonation byproducts are more likely to form some types of DBPs upon chlorination or chloramination (Carlson and Amy, 2001; Shah and Mitch, 2012). However, these general concepts regarding ozonation pertain to treatment of water at the plant.

Ozonation of water that has already undergone treatment, including exposure to a chlorine or chloramine residual in the distribution system *en route* to the building (e.g., hospital) has not been studied to a great extent. Therefore, impacts of ozonation on AOC or DBP formation in a premise plumbing system are still unclear.

Loret et al. (2005) observed corrosion marks on mild and galvanized steel coupons installed in pipe loops for ozone treatment that were similar to corrosion effects caused by other disinfectants (chlorine, chloramine, chlorine dioxide and CSI), except that the coupons exposed to CSI also had copper deposits.

2.3.6.4 Operational Conditions

As water temperature increases, ozone disinfection efficiency increases (USEPA, 1999d). However, because ozone decomposes quickly in hot water, it is difficult to maintain an effective concentration throughout the system to control *Legionella*. Therefore, there is a need to balance the tradeoffs between potentially higher inactivation rates and lower available CT (i.e., disinfectant residual concentration "C" multiplied by contact time "T") with increased water temperature. Due to the faster decomposition of ozone in warm water, water leaving the ozone contactor with a concentration of 1 to 2 mg/L may not have a concentration high enough to inactivate *Legionella* when it reaches distal parts of the system. In the range of 6 to 9, pH will not impact the efficacy of ozone disinfection. However, ozone decomposes faster at higher pH, and as such, there is a lower available CT for a given ozone dose. Carbonate alkalinity also has a considerable impact on ozone decomposition, with increasing alkalinity slowing down ozone decay, and thus increasing the available CT for a given ozone dose.

One important aspect of ozone-based treatment in a building is the potential for ozone residual that reaches the tap to degas from the water and expose building occupants to ozone gas. Edelstein et al. (1982) noted ozone-related odors from the treated water and within the building where ozone treatment was being conducted, but the researchers did not measure airborne ozone concentrations. Ozone is a toxic gas (i.e., it is a principal component of smog). It can corrode steel pipes and fittings, concrete, rubber gaskets and other materials (USEPA, 2007). Due to safety concerns and the corrosiveness of ozone, on-site generation of ozone gas requires containment or a separate structure. Ambient air monitoring may also be required for compliance with local regulations.

Ozone disinfection is a relatively complex process. Operational and maintenance demands are significantly greater than those for chlorine and chloramines (USEPA, 2007).

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3 Other Strategies Used to Control for *Legionella*

3.1 Emergency Remediation

Emergency remediation of a premise plumbing system is triggered by a *Legionella* outbreak associated with a potable water system, identification of suspected cases of the disease associated with a potable water system, identification of *Legionella*-positive water results during routine environmental testing or failure of control measures (ASHRAE, 2015; VHA, 2014). Several agencies and organizations have published standards or guidance documents on when and how to conduct emergency remediation (ASHRAE, 2015; HSE, 2014; VHA, 2014; HSE, 2009; CDC, 2003; ASHRAE, 2000). Some of these documents apply to not only premise plumbing systems but also cooling towers and evaporative condensers; whirlpool spas; decorative fountains; and other aerosol-generating air coolers, humidifiers and air washers. This section provides an overview of commonly used emergency remediation methods, including superheat-and-flush disinfection, shock hyperchlorination, POU filtration and any combination of these methods. Appendix A.1 lists the references cited in Section 3 and the type of study (e.g., lab study, literature review).

3.1.1 Superheat-and-Flush Disinfection

3.1.1.1 Background

The superheat-and-flush disinfection method involves raising the water temperature in the hot water heater sufficiently high to ensure hot water is delivered to outlets; circulating the hot water through all water outlets, faucets and showerheads; and then flushing with the hot water for a suitable period. In building water systems that are not heavily contaminated, a constant hot water heater temperature of 60 degrees C (and 55 degrees at the outlets) is often enough to control (but not necessarily eliminate) *Legionella*, as described in Section 2.2.2.1. For example, Dennis et al. (1984) showed that in a laboratory at 54 degrees C, a 90-percent (1 log) reduction in *L. pneumophila* 74/81 serogroup 1 occurred after 27 minutes. At 58 degrees C the same reduction took only six minutes. Where emergency remediation is required, raising the temperature of hot water tanks to 71–77 degrees C (160–170 degrees F) and keeping the water temperature at outlets >65 degrees C (149 degrees F) during flushing are recommended (Sehulster and Chinn, 2003; ASHRAE, 2000). The optimal flush time reported varies from 10 to 30 minutes depending on the characteristics of the premise plumbing system. A 30-minute flush, first adopted by Best et al. (1983), is recommended as a good practice.

3.1.1.2 Characterization of Effectiveness against *Legionella*

The superheat-and-flush method can be effective as an emergency disinfection procedure for building hot water systems, particularly in hospital outbreak scenarios.

- Best et al. (1983) first reported the use of superheat-and-flush to control *Legionella* from a hospital water supply by raising the temperature of hot water tanks as high as 77 degrees C (170.6 degrees F) for 72 hours and flushing the water outlets for 30 minutes with hot water. After flushing, the number of samples testing positive for *Legionella* was reduced, followed by a decline in the incidence of legionellosis. The temperature of the hot water storage tanks was intermittently increased on eight occasions to 60–77 degrees C (140–170.6 degrees F), resulting in a decrease in the number of months in which cases of Legionnaires' disease occurred and the proportion of nosocomial pneumonias caused

by *L. pneumophila* and Pittsburgh pneumonia agent (now designated *L. micdadei*).

- Darelid et al. (2002) reported the successful application of thermal shock disinfection after a 1991 nosocomial outbreak of Legionnaires' disease in a Swedish hospital. The hot water temperature was raised from 45 degrees C to 65 degrees C (113 degrees F to 149 degrees F) to maintain the circulating hot water temperature greater than 55 degrees C (131 degrees F) to control the bacteria. Environmental monitoring was conducted over a 10-year period to confirm whether this thermal shock treatment was sufficient or if chemical disinfection was required. The monitoring results showed that complete eradication of *Legionella* was not possible, but the occurrence of nosocomial Legionnaires' disease was controlled by maintaining the circulating hot water temperature greater than 55 degrees C (131 degrees F).

However, an inadequate temperature for the superheat (less than 65 degrees C, or 149 degrees F) or a short flush time (such as five minutes) is ineffective for the control of *Legionella*, as experienced at some hospitals (Chen et al., 2005). Even 70 degrees C may allow some bacteria to survive and acquire resistance (Allegra et al., 2011). The shock treatment may not provide long-term control of *Legionella* if the premise plumbing system does not maintain a proper temperature or a residual chlorine level.

- Allegra et al. (2011) tested the heat susceptibility of *Legionella* strains isolated from hot water in four hospital distribution systems over several years. The authors compared susceptibility of each group of strains using samples collected prior to and following heat treatment in the distribution system. They exposed *Legionella* from each sample to 70 degrees C (158 degrees F) for 30 minutes in the laboratory and determined the percentage of viable and VBNC cells remaining using flow cytometry. Strains of *L. pneumophila* serogroup 1 demonstrated highly variable heat resistance (mean percentage of viable and VBNC cells ranged from 11.7 percent to 71.7 percent). One group of strains in one distribution system developed resistance over time, apparently in response to repeated heat shock, with the mean percentage of viable and VBNC cells increasing from 12.7 to 70.5 percent.

- Chen et al. (2005) conducted superheat-and-flush treatment on the water supply for a 1,070-bed medical center in southern Taiwan. The treatment procedure involved removing faucet aerators and showerheads at distal sites, flushing distal sites with cold water for two minutes, and flushing distal sites with hot water at 60 degrees C (140 degrees F) for five minutes. The procedure was conducted once a day for five consecutive days on each portion of the water system. Water samples were collected before treatment and 10 days after treatment. The first heat and flush treatment, performed over an eight-week period, controlled *Legionella* in patient wards and reduced the colonization rate in ICUs from 80 percent to 25 percent. But two months later, the colonization rate had increased from zero to 15 percent in patient wards, and from 25 percent to 93 percent in the ICUs. The second superheat-and-flush treatment, performed over a 2-day period, resulted in much smaller reductions in the colonization rate.

- Stout et al. (1998) compared effectiveness of superheat-and-flush to CSI for controlling *Legionella* in the Pittsburgh Veterans' Affairs Health Care Center. There were an average

of six cases of Legionnaires' disease per year for the 13 years when superheat-and-flush was employed, as compared to two cases per year for the 3 years when CSI was used. The percentage of distal sites positive for *L. pneumophila* was 15 percent for superheat-and-flush compared to 4 percent for CSI. Because the conditions during the two study periods may not have been comparable, the authors used findings from another hospital study for verification (Mietzner et al., 1997). Stout et al. (1998) concluded that a properly maintained and monitored CSI system was more effective than the superheat-and-flush method.

- Mietzner et al. (1997) conducted thermal treatment of a hot water circuit in a hospital by flushing hot water (>60 degrees C, or >140 degrees F) through distal fixtures for 10 minutes. Sampling of the faucets showed that positive samples decreased from approximately 80 percent to 1 or 2 percent of samples immediately following the initial treatment, then increased to 36 percent within 61 days of the treatment. Three additional heat-flush treatments resulted in zero detection of *L. pneumophila*. But recolonization occurred within 29 days of the last treatment. The heat-flush treatment failed to provide long-term control of *L. pneumophila***.**

Combining the superheat-and-flush method with supplemental continuous chlorination (Cristino et al., 2012; Heimberger et al., 1991; Snyder et al., 1990) or UV light irradiation (Liu et al., 1995) has achieved some success in decontaminating hospital water systems.

- Cristino et al. (2012) reported the successful application of various shock disinfection methods (e.g., heat shock, chemical shock with peracetic acid and chlorine dioxide) followed by continuous chlorination for long-term care facilities, including three hot water systems that were colonized by *L. pneumophila* and one hot water system colonized by *L. londiniensis*. No cases of hospital-acquired legionellosis occurred during the study period. Although three of four systems reported that 100 percent of samples were positive for *Legionella* before and after shock treatment, the mean *Legionella* count was reduced by up to 69 percent as a result of shock disinfection. Two years of environmental monitoring after shock disinfection showed that *Legionella* counts either continued to decrease or remained at post-treatment levels.

- Liu et al. (1995) conducted superheat-and-flush and shock chlorination treatment prior to UV treatment of a hospital's hot and cold water systems. Five years of surveillance data at untreated control sites (three showers and 20 other water outlets) showed that 30–80 percent of sites were persistently colonized with *L. pneumophila* (i.e., 1–300 CFU per swab). The UV treatment units were located near points of use such as showers. Filters were added to prevent scale accumulation on the UV lamps. The study showed that UV plus pre-filtration could prevent *Legionella* recolonization for three months after shock treatment.

- Heimberger et al. (1991) reported the successful application of hot water flushing and supplemental chlorination to control *Legionella* at a tertiary care hospital in Syracuse, New York. *L. pneumophila* was found in 6 of 32 water samples, including samples from one of two hot water tanks. Initial treatment of the hot water system included tank cleaning, hot water flushing and shock chlorination but did not include continuous

supplemental chlorination. One month after initial treatment, *L. pneumophila* was again detected from a hot water tank and several taps, and another case of legionellosis occurred. In response, hot water flushing, shock chlorination and continuous supplemental chlorination were conducted. On a monthly basis, each hot water tank is taken offline, cleaned and treated with hot water. In the 7.5 months after these practices were employed, all samples were negative for *Legionella* and no new cases of legionellosis had occurred.

- Snyder et al. (1990) reported a successful application of heat flushing followed by continuous supplemental chlorination to reduce *L. pneumophila* in a hospital hot water system. Twelve of 74 sampling sites in the hot water system were culture-positive for *L. pneumophila*. Heat flushing (>60 degrees C, or >140 degrees F) at hot water system outlets for 30 minutes alone reduced the number of *Legionella*-positive samples by 66 percent, but within four months, the number of positive samples had increased. Continuous supplemental chlorination was added to the hot water system at a dosage rate of 2 mg/L. After six weeks, the number of *Legionella*-positive samples decreased from 37 percent (43 of 115 samples) to 7 percent (8 of 115 samples). After 17 months of continuous supplemental chlorination, no new cases of legionellosis had occurred.

3.1.1.3 Potential Water Quality Issues

Regrowth of *Legionella* following superheat-and-flush has been identified as an issue (Chen et al., 2005; Stout and Yu, 2003). Recolonization could be caused by the survival properties of *Legionella* (i.e., the ability to colonize biofilms, ability to parasitize and multiply within protozoa, and ability to enter a VBNC state, as discussed in Section 1.2.3), or failure to properly address the conditions that caused the problem (such as dead ends and long water residence times). Researchers have revealed that *L. pneumophila* can rapidly proliferate after temperatures are lowered, presumably via microbial response to the nutrients released by the newly killed biofilm (necrotrophy) (Temmerman et al., 2006). This finding indicates that disturbing the microbial ecology on a short-term basis may exacerbate pathogen regrowth in the long-term (Pruden et al., 2013). EPA advises facility owners or operators who are considering adjustments to their premise plumbing system to consult with their primacy agency for any specific considerations or requirements that may apply including plumbing code requirements. See Section 2.2.2.1 for additional information on a temperature approach for *Legionella* control.

3.1.1.4 Operational Conditions

The superheat-and-flush method generally does not require special equipment; however, it is labor-intensive and time-consuming (Chen et al., 2005) due to the need to monitor hot water temperature and flushing time. Several limitations of the superheat-and-flush method need to be recognized:

- Superheat-and-flush is only effective when the water temperature at distal outlets reaches the required temperature and the flushing is conducted for the required duration (Chen et al., 2005). Superheat-and-flush requires sufficient hot water heating capacity (HSE, 2014).

- Superheat-and-flush requires considerable energy and manpower resources.

- Thermal disinfection will not disinfect downstream of thermostatic mixer valves and so is of limited value where such valves are installed (HSE, 2009).

- Scalding is a significant hazard (HSE, 2014; Health Canada, 2013; WHO, 2011). Caution and close supervision must be taken during emergency disinfection to protect patients, staff and visitors from scalding.

Recommendations for conducting an effective superheat-and-flush, based on the published standards and guidelines (HSE, 2014; VHA, 2014; HSE, 2009; CDC, 2003; ASHRAE, 2000), are summarized as follows:

- When possible, perform flushing when the fewest building occupants are present (e.g., nights and weekends).

- Post signage and warning notices at all areas of the building to alert occupants of the potential scalding hazard.

- Maintain water heater temperatures at 71–77 degrees C (160–170 degrees F) while progressively flushing each outlet in the system for up to 30 minutes at 65 degrees C (149 degrees F).

- Flushing multiple outlets simultaneously can save time, but should not exceed the capacity of the water heater and the flow capacity of the system.

- Perform flushing in a manner that reduces the risk of scalding and aerosolization of potable water in patient-care areas.

- Following superheat-and-flush treatment, maintain hot water system temperature >60 degrees C (140 degrees F) in all hot water lines.

- At the end of the procedure, collect samples of water at distal outlets of the water system. After the water temperature has returned to normal, *Legionella* culture should be performed within two to seven days to determine efficacy of the treatment; the delay in testing is intended to reduce false negative results caused by VBNC cells (HSE, 2014). Culture should be repeated within two weeks of treatment to determine if there is any short-term control. Repeat the procedure until decontamination is achieved. Following decontamination, microbiological checks must be repeated periodically.

3.1.2 Shock Hyperchlorination

3.1.2.1 Background

Hyperchlorination involves injecting chlorine at an elevated concentration into the premise plumbing system in one of two modes: shock or continuous hyperchlorination. Shock hyperchlorination, often used for emergency disinfection, is the injection of chlorine to achieve a level of 20–50 mg/L of free chlorine (as chlorine) (HSE, 2014; VHA, 2014). After a sufficient

contact time, the water is flushed and the residual chlorine is returned to its normal level. Continuous chlorination (sometimes called continuous hyperchlorination) is accomplished by continuous injection of chlorine to achieve at least 0.5–1.0 mg/L (as chlorine) free chlorine (HSE, 2014). It is often performed as a post-emergency disinfection procedure to aid the control of *Legionella* and biofilms. Continuous hyperchlorination in premise plumbing systems is discussed in Section 2.3.1.

3.1.2.2 Characterization of Effectiveness against *Legionella*

Hyperchlorination can be applied to the cold- and hot-water tanks and to the entire premise plumbing system. It may be the only option in some healthcare facilities where superheat-and-flush cannot be used because hot water lines are not available at every distal site or they cannot reach the required high temperature.

The success of hyperchlorination in the control of *Legionella* has been mixed, as shown in the case studies described later in the document and other studies in Section 2.3.1:

- García et al. (2008) conducted long-term surveillance and studied the persistence of *L. pneumophila* in finished water systems at a hospital and a hotel before and after multiple hyperchlorination treatments. Each facility had been associated with cases of Legionnaires' disease. Prior to May 1998, the hotel's finished water system was interconnected with the industrial water system. Over the period August 1992 to April 2001, at least seven hyperchlorination treatments were applied using a dosage rate of 10 mg/L and contact time of five hours, or a dosage rate of 20 mg/L and contact time of eight hours. Between 1984 and 1995, the hospital's water system was treated with hyperchlorination four times (dosage rate and contact time not stated by authors). Environmental monitoring after each treatment showed that legionellae were absent for a period of a few months. New cases of Legionnaires' disease also occurred after hyperchlorination. The results of *Legionella* testing also demonstrated that successive hyperchlorination treatments did not modify the susceptibility of bacteria to new treatments with chlorine or other disinfectants. The authors noted that interaction with other microorganisms, such as amoebae, could favor the persistence of *L. pneumophila*, as noted in a previous investigation by Kilvington and Price (1990).

- Despite shock hyperchlorination (with 50 mg/L) being applied to the cold- and hot-water tanks and to the whole premise plumbing system, *L. pneumophila* colonization persisted in a 250-bed hospital (Biurrun et al., 1999). A continuous chlorine system was installed in the cold-water tanks to achieve approximately 0.8 mg/L of free residual chlorine at the cold-water outlets (higher levels of chlorine and thermal treatment were not desired due to the poor condition of the piping). This, along with elimination of dead ends, replacement of contaminated fixtures, and other corrective measures, reduced the number of positive sample sites from 88 percent to 17 percent. But one month later, colonization was detected at a positive rate of 58 percent.

- Grosserode et al. (1993) reported a 10-year follow-up study of the efficacy and environmental effects of hyperchlorination for control of nosocomial legionellosis at a university hospital. In the 10 years following an outbreak in 1981, the incidence fell dramatically from 35 to less than 1 per 1,000 admissions; the frequency of cases of

legionellosis also declined significantly from 16 cases among 21 tested to 5 cases among 294 tested. No legionellae were isolated from the more than 500 water samples collected during the 10-year period.

In general, the efficacy of shock hyperchlorination is affected by the same factors as continuous hyperchlorination, as described in Section 2.3.1. Shock hyperchlorination, if conducted alone, would not achieve long-term control of *Legionella.* Researchers reported that *Legionella* could be protected within free-living protozoan cysts of *Acanthamoebae*, which can survive free chlorine concentrations up to 50 mg/L (Storey et al., 2004a; Kilvington and Price, 1990).

3.1.2.3 Potential Water Quality Issues

Regrowth of *L. pneumophila* may occur within days or weeks after shock hyperchlorination is discontinued (Cooper and Hanlon, 2009), just as with the superheat-and-flush method. Multiple shock hyperchlorination treatments may be needed in response to positive potable water cultures, followed by continuous hyperchlorination or other treatment measures to achieve long-term results.

Caution must be taken during shock hyperchlorination to avoid exposures to high disinfectant levels. Signs and warning labels should be posted at sinks and other outlets to warn the building occupants not to use the water (HSE, 2014). When possible, shock hyperchlorination should be performed when the fewest building occupants are present (e.g., nights and weekends).

3.1.2.4 Operational Conditions

Recommendations for conducting effective shock hyperchlorination, based on published guidelines (HSE, 2014; HSE, 2009; ASHRAE, 2000; Grosserode et al., 1993), are summarized in this section:

Shock hyperchlorination of hot and cold water systems can significantly impact the physical integrity of the piping system and water fixtures if applied incorrectly or too often. Corrosion of metal pipes and appurtenances may occur from exposure to high levels of free chlorine (CDC, 2003). Therefore, routinely performing these procedures is not recommended (HSE, 2014).

Other recommendations include the following:

- Post signage and warning notices at all areas of the building to alert occupants of the potential chemical hazard.

- When possible, shut off and bypass any existing water treatment equipment (e.g., water softeners, carbon filters).

- Clean the tanks and associated fittings. Remove sediment, sludge and stagnant water. Correct other problems that may allow harboring of *Legionella.* For instance, fixtures and fittings that contain rubber may facilitate growth of *Legionella*. Rubbers containing thiuram disulfide do not enhance the growth of *Legionella*, and some have suggested the use of such rubber in water systems (Niedeveld et al., 1986).

- To prevent colonization from recurring after emergency disinfection is discontinued, the initial conditions that caused the problem (such as long water residence times) need to be identified and corrected; the water temperature needs to be maintained at a proper level (>60 degrees C, or 140 degrees F); or a residual disinfection treatment needs to be installed for long-term routine operation.

- Consider the use of continuous hyperchlorination, or another form of long-term treatment if cases continue to be identified or if a *Legionella* strain isolated from patients persists in the premise plumbing system. If *Legionella* isolates are limited to the hot water system, continuous hyperchlorination should be initiated for the hot water system alone. Chlorine levels need to be adjusted as required to keep DBPs at acceptable levels.

- Monitor the hyperchlorinated premise plumbing system for pipe damage. Assays for levels of copper, lead and iron, along with use of corrosion and water stability indexes, may permit early detection and control of corrosion problems.

3.2 Point-of-Use Filtration

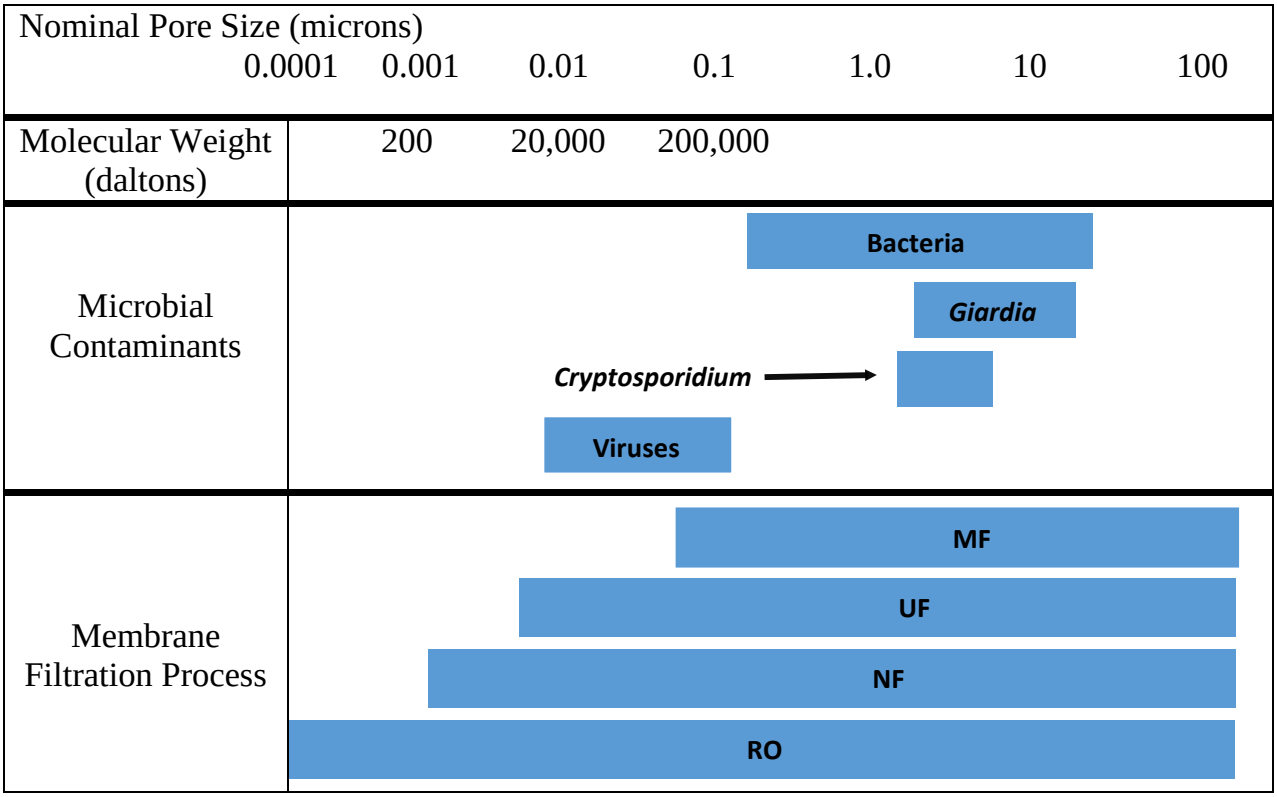
3.2.1 Background

POU filtration is defined as the use of a device applied to a single tap for the purpose of reducing contaminants in drinking water at that one tap. POU filtration can be used at specific taps, faucets and showerheads as a temporary measure to provide a physical barrier against *Legionella*. Hospitals have used this technology to try to reduce disease transmission (Ortolano et al., 2005). POU water filtration may be an effective measure for remediation situations if a limited patient area can be targeted. Filters can be installed immediately and are a better alternative than restricting showering and providing bottled water.

Advances in membrane filter technology have resulted in POU filtration systems capable of removing microorganisms (USEPA, 2005c; USEPA, 2001). These treatment systems include microfiltration (MF), ultrafiltration (UF), nanofiltration (NF) and reverse osmosis (RO) processes. MF and UF use hollow-fiber membrane material contained in cartridges that separate particles using a sieving mechanism based on the pore size and particle size. NF and RO use spiral-wound (consisting of a flat sheet of membrane material wrapped around a central collection tube) filter elements or cartridges. They are semi-permeable membranes without definable pores. NF and RO are both pressure-driven systems that function similarly in their removal mechanisms for microbial contaminants. Exhibit 3-1 describes the average pore size and molecular weight cut-off requirements for different membrane filtration devices. For comparison, *Legionella* cells are typically 0.3–0.9 micrometers (µm) wide and 2–20 µm long when grown in laboratory culture (WHO, 2007).

Though ozone and UV may also be applied at the POU, this literature review does not include information regarding POU application for these technologies.

Exhibit 3-1: Membrane filtration guide for removal of microbial contaminants



Source: USEPA, 2005c.

EPA defines two criteria for membrane filtration technology for pathogen removal under the Safe Drinking Water Act's (SDWA) Long Term 2 Enhanced Surface Water Treatment Rule (40 CFR 141.2):

- The filtration system must be a pressure- or vacuum-driven process and remove particulate matter larger than 1 µm (for *Cryptosporidium*, specifically) using an engineered barrier, primarily via a size exclusion mechanism.

- The process must have a measurable removal efficiency for a target organism that can be verified through the application of a direct integrity test.

Many home owners; facility owners; and operators of hospitals, nursing homes and hotels utilize POU membrane filtration devices, often in a proactive manner but also in response to emergencies (USEPA, 2006d). Some hospitals use POU membrane filtration treatment in areas populated with high-risk patients (e.g., in oncology wards, bone marrow and solid organ transplant units, and ICUs).

Two ANSI standards exist for certification of POU devices used for removal of microbial contaminants: Standard 53 (Drinking Water Treatment Units – Health Effects) and Standard 58 (Reverse Osmosis Drinking Water Treatment Systems). POU filtration devices have been certified by NSF International for removal of protozoa, bacteria and viruses in general, using surrogate microorganisms as challenge organisms during testing and evaluation. Lists of POU

devices certified by independent, accredited laboratories to meet these standards are available from Underwriters Laboratories (www.ul.com), NSF International (www.nsf.org/certified/dwtu) and the Water Quality Association (www.wqa.org). Note that although some POU filtration devices have been certified to meet bacterial removal standards, they have not been certified specifically for removal of *Legionella.*

3.2.2 Characterization of Effectiveness against *Legionella*

Several case studies describe the effectiveness of POU membrane filtration devices for removal of *Legionella.*

- Casini et al. (2014) reported the efficacy of POU filtration installed in selected wards of an Italian hospital to further reduce *Legionella* growth within the building hot water system after chloride dioxide disinfection. POU filters used in this study had a 0.2-µm nominal pore size and 30-day replacement rate. This integrated disinfection-filtration strategy, although expensive, significantly reduced *Legionella* counts to less than 10^3 CFU/L and achieved a positive sample rate of less than 30 percent.

- Baron et al. (2014b) evaluated a new faucet filter at five sinks in a cancer center and found that legionellae were removed from all filtered samples for 12 weeks, exceeding the manufacturer's recommended maximum duration of use of 62 days. The filters contain a 30-µm pre-filtration layer, a 1-µm membrane and a 0.2-µm membrane.

- Marchesi et al. (2011) performed a 10-year review of multiple treatment methods to control for *Legionella* at a hospital in Italy, including POU filtration, though information on the characteristics of the filters was not supplied. Filters were placed in high-risk units of the hospital only, where high levels of *Legionella* contamination were identified, and were replaced every 30 days. No legionellae were detected at taps containing POU filters.

- Daeschlein et al. (2007) evaluated a reusable POU filter for removing waterborne pathogens, including *L. pneumophila*, in a hospital's transplant unit for eight weeks. Filters had three configurations: (1) hollow fiber of polyethersulfone with pore size 0.2 µm and surface area of 800 cm^2; (2) hollow fiber of polyethersulfone with pore size 0.2 µm, surface area of 1100 cm^2, and inner encasement coated with nanosilver; and (3) same as (2) with metallic silver outlet.

  Filters were placed on 18 taps (12 taps, six showers) in the hospital's transplant unit and each filter was monitored for pathogens at one, four and eight weeks, reprocessed and re-used in three additional trials. Over the test period, no *Legionella* or other pathogens were detected in any filter effluent. Because bacterial counts in filtered water exceeded the limit of >100 CFU/mL eight times, the following criteria were developed to prevent carry-over contamination from re-use of the filters: filters were cleaned with a strong chemical followed by flushing and thermal disinfection in a quality control-compliant washer-disinfector once a week, in addition to alcohol disinfection of the filter encasement. With this reprocessing, the authors determined that filters should be changed after four weeks in high-risk areas and after eight weeks in moderate-risk areas.

- A newer version of the filters described in the example by Daeschlein et al. (2007) was evaluated by Vonberg et al. (2008) at a hospital in Germany. The new version had a membrane surface coated with nanosilver. Fifteen taps in a thoracic surgery department were selected and sampled before adding filters. Filters were placed on those taps and sampled after one, two, three and four weeks of usage. Samples were analyzed for the pathogens *Legionella* and *Pseudomonas,* in addition to the indicators enterococci and heterotrophic bacteria. Legionellae were detected in nearly half (48.3 percent) of taps before filters were added and only one sample (week 1) after filters were added (*L. pneumophila* serogroup 1, 4 CFU/mL); no *Pseudomonas* were detected. The authors did not attempt to reprocess the filters as in the Daeschlein study and did see heterotrophs increase to >100 CFU/mL in some filters after one week of use. The authors concluded that incorporation of nanosilver in the filter's membrane surface coating may prevent biofilm growth in this POU device and that use of these POU filters with weekly replacement in high-risk patient wards may be effective at preventing nosocomial legionellosis.

- Sheffer et al. (2005) evaluated POU filtration devices containing positively charged nylon membranes with a 0.2-µm nominal pore size. Filters were placed on four taps in the administration building at a hospital and monitored for *Legionella*, heterotrophic bacteria, and *Mycobacteria*, along with three taps without filters, every 2–3 days for 13 days, before and after a one-minute flush. Samples from taps with filters before flush were negative for *Legionella* during the 13-day period, while mean concentration in taps without filters was 104.5 CFU/mL. *Mycobacterium gordonae* was isolated from 10.3 percent of taps without filters before flushing, but no *Mycobacteria* were isolated from taps with filters before flushing. Heterotrophs were significantly reduced at taps with filters. One post-flush sample from a tap with a filter was positive for *Legionella* on day 10, with a concentration of 5 CFU/mL. No post-flush samples from taps with or without filters were positive for *Mycobacteria*. The authors concluded that the POU filters used in this study effectively controlled *Legionella* and *Mycobacteria* through seven days of use.

- Molloy et al. (2008) evaluated three types of POU solid block activated carbon filters for removal of *L. pneumophila* in a laboratory-simulated domestic water system: (1) carbon containing copper, (2) carbon containing copper and silver and (3) carbon without metals. Filters were challenged with tap water seeded with *L. pneumophila* multiple times and water was monitored under simulated domestic use for six weeks. Levels of *Legionella* were reduced by all three filters by nearly 8 log (99.999999 percent), but they were detected in all filter effluents for the length of the study. The authors concluded that the organisms attached to the carbon blocks and sloughed off over time.

3.2.3 Potential Water Quality Issues

POU filters have the potential to concentrate bacteria (Molloy et al., 2008) and foster growth of pathogens (Daeschlein et al., 2007; Sacchetti et al., 2015), especially if devices are not properly maintained. Failure of filters could lead to the release of high levels of pathogens. Membranes may foul (Warris et al., 2010) or be degraded by microorganisms.

3.2.4 Operational Conditions

In general, most POU devices include pre-filtration (usually granular activated carbon) to treat inlet water and prevent clogging of the central membrane, the central filtration membrane and post-filtration, in a module configuration. Design guidance for POU filtration devices can be found in EPA's Membrane Filtration Guidance Manual (USEPA, 2005c). Facility owners and operators are advised to follow the manufacturer's operational guidance for the POU system being employed. There is a variety of commercially available systems with unique design features and operational conditions. Additional guidance on operation and maintenance for POU treatment devices, including examples of maintenance logs, can be found in EPA's POU or POE Treatment Options for Small Drinking Water Systems (USEPA, 2006d). A detailed maintenance log should be kept for each system, based on the state's requirements, if any. Maintenance typically includes the following:

- Tracking flows – Flow meters are used to measure the total flow treated, as flow values may be used to determine filter membrane or other component replacement parameters.

- Replacement parts – Components should be replaced as required by the manufacturer or monitoring data, to ensure water free of microbial contaminants. Minimal components needing regular replacement include exhausted membranes and pre- and post-filters. A 30-day replacement rate was reported in the studies using POU filters for *Legionella* control in hospitals (Casini et al., 2014; Marchesi et al., 2011).

- Visual check of mechanical conditions – All components, including the mechanical warning device, should be inspected visually on a regular basis and parts replaced/repaired if necessary, in addition to being replaced as specified by the routine replacement schedule.

4 Questions and Answers on *Legionella* Control in Premise Plumbing Systems

4.1 Public Health Concerns

Q1. What are the threats from *Legionella* in a premise plumbing system?

Legionella spp. are naturally occurring bacterial pathogens that can be present in municipal and other water supplies. Premise plumbing systems may provide conditions (e.g., long water residence times, water temperatures favorable (e.g., warm) for *Legionella* growth and low disinfectant residual levels) that favor growth of *Legionella* to levels that may result in increased risk to public health. For additional information please see Section 1.2 of this document.

Q2: Do all species of *Legionella* cause disease?

Although most of the diagnosed cases of legionellosis (Legionnaires' disease and Pontiac fever) are associated with *Legionella pneumophila* (serogroup 1), approximately half of all the species of *Legionella* have been associated with clinical cases of legionellosis. However, it is probable that most legionellae can cause human disease under the appropriate conditions (e.g., in individuals in higher risk groups) (Borella et al., 2005a; Fields, 1996; Fang et al., 1989). For additional information, please see Section 1.2 of this document.

Q3. Do you need to eliminate all legionellae in order to have a safe building environment?

Not necessarily. Due to the highly variable and inconclusive information that is available, it is not feasible to establish a definitive action level below which the risk from disease is eliminated.

Facility owners or operators may choose to assess the population they serve for individual factors that may increase the risk of disease (e.g., age, immunosuppression) to reduce the risks from legionellae. See Section 1.2.2 for additional information on risk factors. The facility owner/ operator may want to evaluate the premise plumbing system processes that could contribute to *Legionella* growth (e.g., long water residence times and low disinfectant residual levels). This assessment should allow the facility manager to determine the necessary stringency of the risk management plan and measures (see Section 2.2 for additional information).

4.2 Potential Regulatory Requirements

Q4. What constitutes being a regulated public water system?

The criteria for being a regulated public water system (PWS) are provided in SDWA Section 1411 and 40 CFR 141.3. Where there are questions about the application of these criteria, the primacy agency (typically the state) will make the determination based on these criteria and any relevant site-specific considerations.

Q5. Will a building that installs a treatment specifically designed for *Legionella* and serves a population above the threshold of a PWS definition be subject to SDWA requirements?

See response to Question 4.

Q6. Do I need to comply with drinking water standards if I'm only treating the hot water (not for drinking purposes)?

If you have been determined to be a regulated PWS you have to comply with applicable drinking water standards (see response to Question 4). EPA considers water for human consumption to include water for bathing, showering and dishwashing as well as water for drinking, food preparation, brushing teeth and hand washing (see 40 CFR 141.801 and 63 FR 41940, Aug. 5, 1998), independent of its temperature.

Q7. If I comply with the Federal Insecticide, Fungicide and Rodenticide Act (FIFRA) pesticide requirements, am I in compliance with the Safe Drinking Water Act (SDWA) requirements?

No. The pesticide requirements under FIFRA are independent of the SDWA requirements. Each mandate targets complementary, yet different, environmental and public health protection objectives. Registration of a pesticide product or regulatory compliance of a pesticide device under FIFRA does not mean that it meets the requirements of other environmental and public health protection statutes, including the SDWA or vice versa.

The objective of FIFRA is to protect human health and the environment through regulation of pesticide distribution, sale and use. All pesticides distributed or sold in the United States must be registered (licensed) by EPA, unless exempt. Registration assures that pesticides are properly labeled and that, if used in accordance with their approved labeling (USEPA, 2013b), they will not cause unreasonable adverse effects on the environment or human health.

Stakeholders should note that antimicrobial pesticide registrations are specific to pests, use sites and use patterns. For instance, a product registered as a disinfectant for control of *Legionella* in cooling towers cannot be sold or distributed for use in other sites for which it is not registered (i.e., for control of *Legionella* in PWSs).

The SDWA is the main federal law that ensures the quality of Americans' drinking water. Under the SDWA, Congress directs EPA to set national standards to protect public health, but allows states, tribes and territories to seek EPA approval for primary responsibility to implement and enforce these regulations. EPA maintains oversight of the states', tribes' and territories' drinking water programs, including independent federal enforcement authority in primacy states.

While there are no requirements under SDWA that prohibit the installation of a given technology, the primacy agency is typically responsible for accepting the installation or usage of new technologies in PWSs. Both SDWA and FIFRA allow states to have stricter standards than those prescribed in federal regulations. This includes the authority to request additional data or information before approving a drinking water treatment technology or pesticides (see response to Question 8 for additional information) to be used within the state. In the case of a pesticide, a state can require compliance with a state-specific pesticide registration process in addition to the EPA registration. With regard to technologies for drinking water treatment, primacy agencies and technology manufacturers can refer to EPA's Water Supply Guidance (WSG) 90 (USEPA, 1996) for guidance on some of the types of data or information that may be requested as part of the primacy agency's evaluation and approval of alternative drinking water treatment technologies.

Q8. What are the pesticide registration requirements related to pesticide products and devices for the control of *Legionella* (and other microbial contaminants)?

Pesticide products and devices that make antimicrobial claims of efficacy against *L. pneumophila* are subject to certain EPA regulatory requirements. FIFRA defines a pesticide as any substance or mixture of substances intended for preventing, destroying, repelling or mitigating any pest. The term pesticide includes antimicrobials (e.g., sanitizers and disinfectants) in addition to various other substances used to control pests. Products that contain a substance or mixture of substances and that make a pesticidal claim must be registered by EPA prior to sale or distribution, unless exempt. For products that claim efficacy against a public health pest, an applicant must submit data demonstrating that efficacy to obtain a registration.

While devices are subject to certain EPA regulatory requirements, they do not require registration as pesticide products. A pesticide device is defined in FIFRA as an instrument or contrivance (without a chemical substance) that is used to destroy, repel, trap or mitigate any pest such as insects, weeds, rodents, animals, birds, mold/mildew, bacteria and viruses. Devices include instruments or contrivances such as ultraviolet light systems, ozone generators, water filters, etc. A device is subject to the FIFRA prohibition against misbranding and must be produced in an EPA-registered establishment. Additional information on pesticide devices and the associated FIFRA requirements is available on EPA's website and in the Pesticide Registration Manual.

4.3 Control Measures

Q9. What measures can a facility owner or operator take to control the colonization and amplification of *Legionella* in a premise plumbing system?

Buildings can vary in their characteristics (e.g., dimensions, location with respect to the servicing PWS) as well as their purposes. The appropriate measures depend on those characteristics and purposes. A risk management approach, including good design and engineering, can ensure a comprehensive preventative method is followed to address potential health risks related to the premise plumbing system. See Section 2.2 of this document for information on risk management approaches. For additional information on how to develop and implement a risk management program to reduce risks from *Legionella* in premise plumbing systems see the CDC's guidance, Developing a Water Management Program to Reduce Legionella Growth & Spread in Buildings: A Practical Guide to Implementing Industry Standards (CDC, 2016).

Q10. Does EPA regulate *Legionella*?

EPA regulates *Legionella* under the Surface Water Treatment Rule (SWTR). The SWTR has treatment technique requirements to control for *Giardia* and viruses. The SWTR's treatment technique requirements presume that if sufficient treatment is provided to control for *Giardia* and viruses (i.e., 3-log (99.9-percent) inactivation of *Giardia* and 4-log (99.99-percent) inactivation of viruses), then *Legionella* risks will also be controlled. In addition, the Revised Total Coliform Rule (USEPA, 2013a) and the Ground Water Rule (USEPA, 2006a) have treatment technique requirements that address bacteria. Corrective actions related to treatment technique violations may provide some control of *Legionella*. All of these rules apply to PWSs. They would not apply to premise plumbing systems unless the facility is a regulated PWS. See response to Question 4.

Q11. What treatment technologies does EPA approve for control of *Legionella* in drinking water?

EPA does not approve any treatment technologies specifically for control of *Legionella* in drinking water. See response to Question 17.

Q12. What is supplemental disinfection?

For the purposes of this document, supplemental disinfection refers to any additional treatment, such as that added to reduce *Legionella*, used to supplement or boost the treatment provided by the distributor of the water being received. To address water quality and pathogen control needs, facility operators and owners, after a careful review of the premise plumbing system conditions, may wish to implement a supplemental application of a disinfectant specific to and within the premise plumbing system.

Q13. What happens if I add supplemental disinfection in my building?

If a decision to add treatment to the premise plumbing system seems likely, EPA advises facility owners and operators to consult with their primacy agency to determine if any SDWA requirements apply; in addition, there may be state or local requirements that apply. You may also wish to consult with your water supplier (i.e., PWS) to better understand any potential water quality issues before making treatment-related decisions. See Section 1.4 for additional information.

Q14. What should I do before I consider supplemental treatment as a risk management measure?

Assuming facility owners and operators have already identified and begun to address underlying premise plumbing system deficiencies that may lead to *Legionella* risks (see Section 2.2 for more information on Risk Management Approaches), those considering the addition of a supplemental system are encouraged to contact their primacy agency, the PWS and other state and local authorities and familiarize themselves with applicable federal, state and local regulations (e.g., building codes, local health codes). Facility owners and operators should also become familiar with the characteristics and needs of their system to help determine the most appropriate action (e.g., implementing a risk management approach and/or control technologies). Please see Section 2.2 on for more information on risk management approaches and Section 2.3 of this document for more information on control technologies that could be used as supplemental treatment.

Q15. Are there any advantages to supplemental disinfection?

Facilities that design, operate, control and monitor supplemental treatment systems are trying to help ensure that a high level of water quality is maintained, thereby improving public health protection. Providing supplemental disinfection may help maintain the high level of water quality throughout the premise plumbing system.

Q16. Are there any disadvantages to supplemental disinfection?

Operating supplemental water treatment requires the commitment of financial, physical and staff resources to monitor the treatment process (e.g., disinfection byproducts formation, corrosion), to ensure proper function and *Legionella* control. Other disadvantages may include formation of

disinfection byproducts, corrosion of piping or possible degradation of piping materials. An additional disadvantage is that installation of supplemental treatment could lead to a false sense of security. For example, installation of supplemental treatment does not negate the need for facility owners or operators and customers to respond to water supply emergencies (i.e., boil water advisories, "do not consume" notices, "do not use" notices) issued by the selling system.

4.4 New Technology Approval

Q17. What is EPA's process for approval of treatment technologies to control *Legionella* in drinking water?

Technologies that have antimicrobial claims (e.g., control of *Legionella*) need to comply with registration or other requirements for pesticide products and devices under FIFRA (see response to Question 8).

The EPA does not have an approval process for drinking water treatment technologies under SDWA. Rather, the Agency recognizes technologies used for drinking water treatment for their capacity to achieve treatment technique requirements for control of pathogens (under rules such as the SWTR, GWR and LT2ESWTR). The EPA defers to the primacy agency for the approval of technologies that PWSs can use to comply with treatment technique regulations. EPA, in cooperation with the Association of State Drinking Water Administrators, state drinking water program personnel, industry representatives and other stakeholders, developed a Water Supply Guidance document (WSG 90) (USEPA, 1996) that provides a streamlined protocol to facilitate consistent state approvals of new drinking water treatment technologies. WSG 90 is not meant to replace current state plan review and approval processes.

Q18. How do states approve new treatment technologies for *Legionella* control?

Many states utilize a plan approval or permitting process to approve the installation of treatment at PWSs. For new treatment technologies, many states (47) require conformance to ANSI/NSF Standard 60 and/or 61. In addition, states may require third-party validation of efficacy. States may also use the protocol described in WSG 90 to facilitate consistent state approvals of new drinking water treatment technologies. WSG 90 is not meant to replace current state plan review and approval processes.

If you are planning to install additional treatment in your facility, consult with your primacy agency regarding any additional specific requirements. If you require further assistance, contact the appropriate EPA regional office for additional information. For additional information, please refer to Question 28 (Additional Sources of Information).

4.5 Permitting

Q19. What is the procedure for plan review and permitting to operate a *Legionella* treatment system?

The procedure for plan review and approval or permitting varies from state to state. Some states require a permit to construct/install a treatment system and a separate permit to operate the system. Water system owners and operators should consult with their water provider and primacy agency to find out specific procedures and requirements. Alternatively, contact the appropriate EPA regional office for additional information.

4.6 Sampling and Monitoring

Q20. If I am only treating the hot water, where should I take compliance samples?

SDWA requirements for PWSs apply to any water for human consumption independent of the temperature of the water. Consult with your primacy agency regarding site-specific requirements. Alternatively, contact the appropriate EPA regional office for additional information.

Q21. What type of sampling (based on the selected treatment) will I be required to do?

Consult with your primacy agency regarding applicable sampling requirements. Alternatively, contact the appropriate EPA regional office for additional information.

Q22. What residual disinfectants and disinfection byproducts (DBPs) do I need to monitor?

The Stage 1 D/DBPR and Stage 2 D/DBPR established maximum contaminant levels for DBPs and maximum residual disinfectant levels for disinfectant residuals. They also specify the monitoring requirements that regulated PWSs must perform for residual disinfectants and DBPs (type, frequency and location), which will vary depending on the type of system, population served and type of disinfectants being used. See the Stage 1 and 2 D/DBPR Quick Reference Guide (USEPA, 2010) for more information on these regulations.

Q23. If I choose to use chlorine dioxide as a control technology are there any unique DBP monitoring requirements that are different from chlorine and monochloramine?

Yes. If you are subject to the Stage 1 or Stage 2 D/DBPR requirements you may be required to analyze daily chlorite samples on-site and send monthly chlorite samples to a certified laboratory (see 40 CFR 141.131(b), Footnote 8 in Table). In contrast, if you are using chlorine or monochloramine you may be required to send quarterly samples for total trihalomethanes and certain haloacetic acids.

Q24. Does EPA require *Legionella* testing if treatment for its control is installed? If so, what are the targets for meeting control?

No. EPA does not have requirements for *Legionella* testing. However, state or local agencies may specify such requirements in the permit conditions issued to the facility. In addition, there may be requirements for monitoring of water quality parameters or treatment process parameters on a routine basis.

Q25. If a facility has treatment and has either an outbreak or has *Legionella* test results showing detections, are they required to report to the primacy agency?

If the facility is a regulated PWS, it must comply with 40 CFR 141.75 (a)(5)(i), which states the PWS must report waterborne disease outbreaks potentially attributable to that system to the state as soon as possible but no later than the end of the next business day. Also, there will be reporting requirements defined by the state in response to a waterborne disease outbreak, *Legionella* detection or even water quality conditions that may contribute to an outbreak. Facilities that are not regulated PWSs may be required by the state to share information about an

outbreak or *Legionella* detection with local health authorities. These agencies will be able to assist with response actions.

4.7 Operator Certification

Q26. What qualifications do I need to operate treatment installed at my facility to treat *Legionella*?

It depends on a number of factors, including whether your facility is a regulated PWS, the type of water source and the type of treatment. EPA regulations require certain systems to be operated by qualified personnel who meet the requirements specified by the state (40 CFR 141.70(c)). EPA, in cooperation with states, developed and published guidelines specifying minimum standards for certification and recertification of operators of community and non-transient non-community water systems. These guidelines are currently being implemented through state operator certification programs.

Certain systems that use chemical disinfectants must be operated by qualified personnel who are included in a state register of qualified operators (40 CFR 141.130(c)). In addition, there are state operator certification programs that may apply if your facility is a regulated PWS (see questions in Section 4.2). While the specific requirements may vary, the goal is the same: to ensure that skilled professionals are overseeing the treatment and distribution of safe drinking water. Therefore, before adding treatment, EPA advises that you consult with your primacy agency to determine if your facility is a regulated PWS and what qualifications or certifications you may need to operate the treatment. More information on operator certification is available on EPA's website.

4.8 Unintended Consequences

Q27. What are some of the unintended consequences of installing additional treatment for *Legionella*?

For unintended consequences related to specific treatment technique requirements, please see the subsections in this document entitled "Potential Water Quality Issues" for specific control technologies (see Section 2.3).

4.9 Additional Sources of Information

Q28. How can I obtain additional information on each treatment method?

For additional information on any remaining general questions you can contact:

- Safe Drinking Water Hotline by phone or email at:
  - (800) 426-4791
  - hotline-sdwa@epa.gov
- EPA's Drinking Water Website: www.epa.gov/safewater

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Appendices

A.1 Types of Studies by Technology

This table identifies the type of studies conducted for each of the technologies presented in Sections 2.3 and 3 of this document. Laboratory studies involve model distribution and premise plumbing systems. The table also includes field studies which were conducted in the actual distribution system or premise plumbing system.

	Laboratory Study	Field Study	Distribution System Study	Premise Plumbing System Study	Literature Review or Survey
Chlorine					
Lin et al., 1998a		X		X	
Muraca et al., 1987	X			X	
Kilvington and Price, 1990	X				
Kim et al., 2002					X
Gião et al., 2009	X				
Jacangelo et al., 2002	X				
Kuchta et al., 1983	X				
Saby et al., 2005		X		X	
Dupuy et al., 2011	X				
Storey et al., 2004a	X				
Colbourne and Dennis, 1989					X
Cooper and Hanlon, 2009	X				
Loret et al., 2005	X			X	
de Beer et al., 1994	X				
Cristino et al., 2012		X		X	
Snyder et al., 1990		X		X	
Flynn and Swanson, 2014	X				
Kuchta et al., 1985	X				
Orsi et al., 2014		X		X	
Casini et al., 2014		X		X	
Sarver et al., 2011		X		X	
Castagnetti et al., 2011		X		X	
Hassinen et al., 2004		X			
Kirmeyer et al., 2004			X		X
Grosserode et al., 1993		X		X	
Monochloramine					
Jakubek et al., 2013	X				
Dupuy et al., 2011	X				
Jacangelo et al., 2002	X				
Donlan et al., 2002	X				
Cunliffe, 1990	X				

	Laboratory Study	Field Study	Distribution System Study	Premise Plumbing System Study	Literature Review or Survey
Türetgen 2008	X				
Whiley et al., 2014		X	X		
Wang et al., 2012	X		X		
Loret et al., 2005	X			X	
Lee et al., 2011	X				
Pressman et al., 2012	X				
Coniglio et al., 2015		X		X	
Baron et al., 2015		X		X	
Baron et al., 2014a		X		X	
Duda et al., 2014		X		X	
Casini et al., 2014		X		X	
Marchesi et al., 2013		X		X	
Marchesi et al., 2012		X		X	
Weintraub et al., 2008		X	X	X	
Flannery et al., 2006		X	X	X	
Moore et al., 2006		X	X	X	
Heffelfinger et al., 2003			X	X	X
Kool et al., 2000			X	X	X
Kirmeyer et al., 2004			X		X
Zhang et al., 2002	X				
Loret et al., 2005	X			X	
Edwards and Dudi, 2004					X
Moore et al., 2006		X		X	
Pryor et al., 2004		X	X		
Gomez-Alvarez et al., 2012	X		X		
Chlorine Dioxide					
Dupuy et al., 2011	X				
Loret et al., 2005	X			X	
Jacangelo et al., 2002	X				
Mustapha et al., 2015	X				
Casini et al., 2014		X		X	
Marchesi et al., 2013		X		X	
Cristino et al., 2012		X		X	
Marchesi et al., 2011		X		X	
Zhang et al., 2009		X		X	
Sidari et al., 2004		X		X	
Gates et al., 2009					X
Dietrich et al., 1991		X			
Lin et al., 2011b					X
Yu et al., 2013	X				
Chord et al., 2011		X		X	

	Laboratory Study	Field Study	Distribution System Study	Premise Plumbing System Study	Literature Review or Survey
Yu et al., 2011	X				
Castagnetti et al., 2011		X		X	
Copper-Silver Ionization					
Yahya et al., 1989	X				
Liu et al., 1994		X		X	
Lin et al., 2011b					X
Demirjian et al., 2015		X		X	
Dziewulski et al., 2015		X		X	
Chen et al., 2008		X		X	
Mòdol et al., 2007		X		X	
Blanc et al., 2005		X		X	
Stout and Yu, 2003				X	X
Rohr et al., 1999		X		X	
Liu et al., 1998		X		X	
States et al., 1998		X		X	
Lin et al., 2002		X		X	
Kusnetsov et al., 2001		X		X	
Lin et al., 1996	X				
Landeen et al., 1989	X				
Loret et al., 2005	X			X	
Edwards et al., 1994	X				X
Lytle and Schock, 2008	X			X	
Araya et al., 2004	X				X
Araya et al., 2003a	X				X
Araya et al., 2003b	X				
Araya et al., 2003c	X				
Araya et al., 2001	X				
Knobeloch et al., 1994		X		X	X
Zevenhuizen et al., 1979	X				
Knobeloch et al., 1998		X	X	X	
Hong et al., 2010	X				
Dietrich, 2009					X
Huang et al., 2008	X			X	
Lin et al., 1998b	X				
Shih and Lin, 2010	X			X	
Chen et al., 2013		X		X	
Pedro-Botet et al., 2007		X		X	
Rohr et al., 2000	X				
Ultraviolet Light					
Wright et al., 2012		X			X
Hall et al., 2003		X		X	

	Laboratory Study	Field Study	Distribution System Study	Premise Plumbing System Study	Literature Review or Survey
Franzin et al., 2002		X		X	
Liu et al., 1995		X		X	
Gilpin et al., 1985	X				
Muraca et al., 1987	X			X	
Oguma et al., 2004	X				
Knudson, 1985	X				
Antopol and Ellner, 1979	X				
Ozone					
Steiner et al., 2010	X				
Edelstein et al., 1982		X		X	
Jacangelo et al., 2002	X				
Domingue et al., 1988	X				
Muraca et al., 1987	X			X	
Loret et al., 2005	X			X	
Carlson and Amy, 2001	X		X		
Shah and Mitch, 2012					X
Superheat-and-Flush					
Dennis et al., 1984	X				
Best et al., 1983		X		X	
Darelid et al., 2002		X		X	
Chen et al., 2005		X		X	
Allegra et al., 2011	X	X		X	
Stout et al., 1998		X		X	
Mietzner et al., 1997		X		X	
Cristino et al., 2012		X		X	
Heimberger et al., 1991		X		X	
Snyder et al., 1990		X		X	
Liu et al., 1995		X		X	
Stout and Yu, 2003				X	X
Temmerman et al., 2006	X				
Pruden et al., 2013				X	X
Shock Hyperchlorination					
García et al., 2008		X		X	
Kilvington and Price, 1990	X				
Biurrun et al., 1999		X		X	
Grosserode et al., 1993		X		X	
Storey et al., 2004a	X				
Cooper and Hanlon, 2009	X				
Niedeveld et al., 1986	X				
POU Filtration					
Ortolano et al., 2005					X

	Laboratory Study	Field Study	Distribution System Study	Premise Plumbing System Study	Literature Review or Survey
Casini et al., 2014		X		X	
Baron et al., 2014b		X		X	
Marchesi et al., 2011		X		X	
Daeschlein et al., 2007		X		X	
Vonberg et al., 2008		X		X	
Sheffer et al., 2005		X		X	
Molloy et al., 2008	X			X	
Sacchetti et al., 2015		X		X	
Warris et al., 2010	X	X		X	

A.2 Elements of Hazard Analysis and Critical Control Points

Step 1 – Assemble HACCP Team - Pull together a multidisciplinary team to prepare, develop, verify and implement the plan.

Step 2 – Describe Drinking Water - Describe the utility's drinking water, including its source, treatment, storage, distribution and any existing standards for quality and safety.

Step 3 – Identify Intended Use - Describe how the drinking water is used and the major users.

Step 4 – Construct Flow Diagram - For a comprehensive HACCP plan, this would be a schematic showing sources of water, details of treatment, storage, pumping and distribution to end users. For a HACCP plan directed towards a distribution system, the schematic would be restricted to showing the water flow path from the treatment plant to end users.

Step 5 –Confirm Flow Diagram – Since the flow diagram is a critical element used as a basis for the HACCP plan, its accuracy should be confirmed by the HACCP team.

Step 6 - Conduct a Hazard Analysis - Using the process flow diagram, identify hazards, their likelihood of occurrence, potential consequences and control measures.

Step 7 – Determine the Critical Control Points (CCPs) - For each significant hazard, identify points in the process where the consequences of failure are irreversible.

Step 8 – Establish Critical Limit(s) - Determine critical limits for the CCPs that will trigger a corrective action. A critical limit is a criterion which separates acceptability from unacceptability.

Step 9 – Establish a System to Monitor Control of the CCPs - Establish monitoring points, frequency and responsibility.

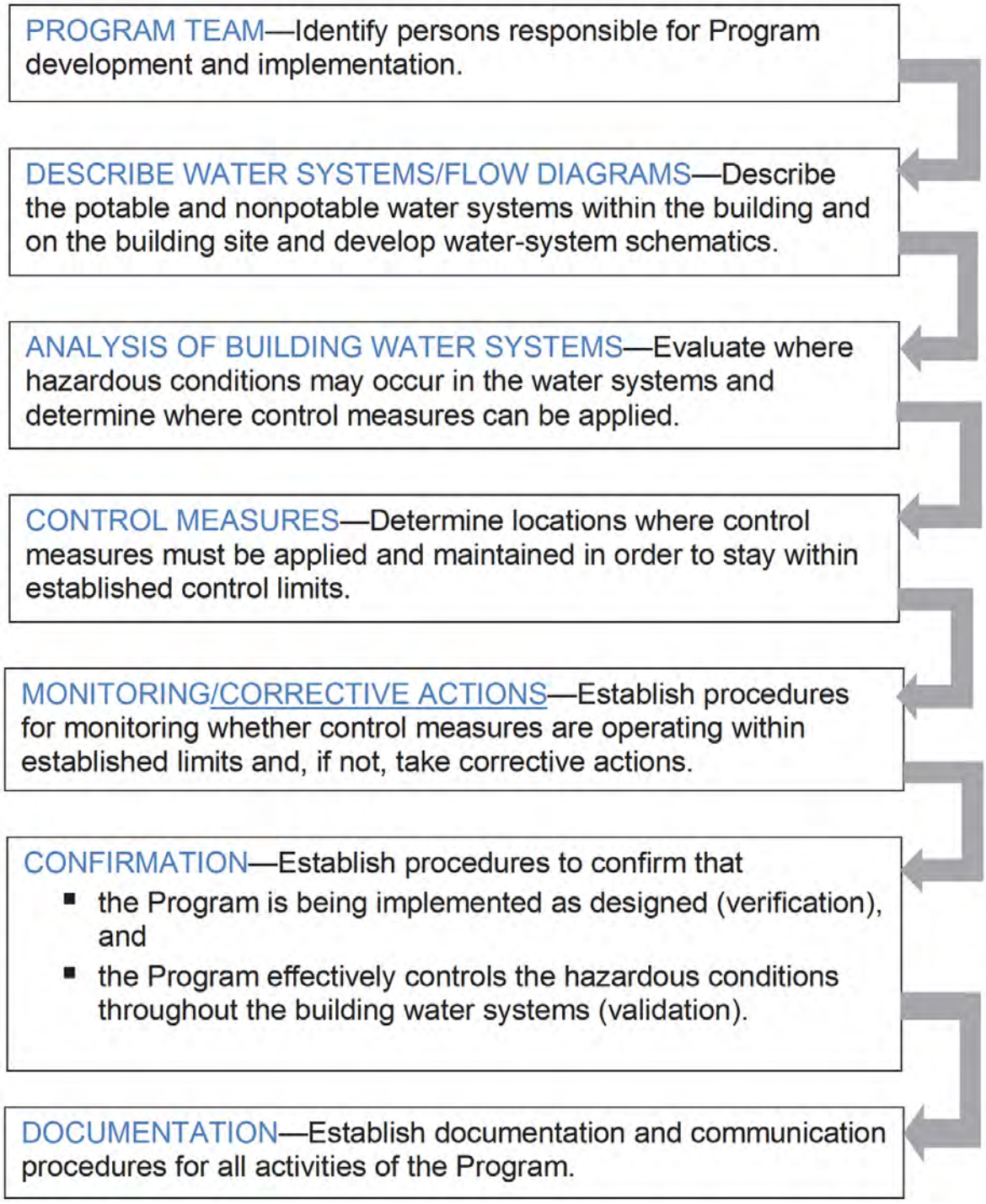
Step 10 – Establish Corrective Actions - Develop plans for follow-up activity when critical limits are exceeded.

Step 11 – Validate/Verify HACCP Plan - Have the HACCP team and other affected parties check the HACCP plan for accuracy, ability to implement and potential effectiveness.

Step 12 – Establish Documentation and Recordkeeping - Develop a record keeping system to track system performance at CCPs.

Source: WHO (1997).

A.3 Elements of a Water Management Program



Source: ASHRAE (2015).

A.4 Water Safety Plan Modules

Module 1 **Assemble team**

Set up a team and decide on a methodology by which a WSP will be developed.

Module 2 **Describe the water supply system**

Visit and thoroughly describe the complete water supply system, from catchment to consumer.

Module 3 **Identify the hazards and assess the risks**

Identify all the hazards and hazardous events that could affect the safety of a water supply from the catchment, through abstraction, treatment, storage, distribution and point-of-use practices to the point of consumption, and assess the risks associated with each hazardous event.

Module 4 **Determine and validate control measures, re-assess and prioritize risks**

Consider if controls or barriers are in place for each hazardous event, check if these controls are effective and re-assess the risks in light of these controls and their effectiveness.

Module 5 **Develop, implement and maintain an improvement plan**

Implement an incremental improvement and upgrade plan where necessary.

Module 6 **Define monitoring of control measures**

Implement plans for ongoing monitoring of controls or barriers to ensure that they continue to work effectively.

Module 7 **Verify the effectiveness of the WSP**

Verify that the WSP as a whole is working effectively to support the consistent delivery of safe and acceptable drinking water.

Module 8 **Prepare management procedures**

Establish and document management procedures, including standard operating procedures (SOPs) and emergency response plans.

Module 9 **Develop supporting programmes**

Establish and document supporting programmes such as operator training, consumer education, optimization of processes and research and development.

Module 10 **Plan and carry out periodic WSP review**

Regularly review and update the complete WSP.

Module 11 **Revise WSP following an incident**

Following any incident or event, consider if it could have been prevented or the impact reduced, determine whether the response was sufficient and effective, and update the WSP to incorporate any identified areas for improvement.

Source: WHO (2009).

A.5 Elements of the American Industrial Hygiene Association Assessment Approach

The American Industrial Hygiene Association suggests that amplification of *Legionella* is one of the links to Legionnaires' disease (AIHA, 2015). "A Routine Assessment… is inherently a proactive effort intended to determine if *Legionella* amplification is occurring in building water systems or other identified sources, or if current control measures are effectively keeping *Legionella* populations in check. An Investigative Assessment… is performed as part of an Outbreak Investigation intended to identify possible sources of *Legionella* amplification and exposure that have caused illness in workers, visitors, residents or members of the public."

Routine Assessment Steps

1. Inventory water systems.
2. Observe and characterize water systems for *Legionella* amplification hazard.
3. Conduct environmental sampling.
4. Identify control measures.

Investigative Assessment Steps

1. Inventory water systems.
2. Observe and characterize water systems for *Legionella* amplification hazard.
3. Conduct environmental sampling.
4. Identify control measures.
5. Perform disease surveillance.

Source: AIHA (2015).