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Draft - Technologies for *Legionella* Control: Scientific Literature Review

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Disclaimer

This draft document was prepared by the U.S. Environmental Protection Agency (EPA) as a technical resource for primacy agencies, building water system operators, and building owners to consider as they evaluate technologies to respond to the risks associated with *Legionella* colonization of premise plumbing. This draft document is a summary of publicly available, peer-reviewed, technical literature that evaluates the effectiveness of six technologies used for *Legionella* control. The draft document also discusses water quality issues that could result when using the various approaches, and summarizes operational conditions for each technology. It also discusses critical multiple-barrier approaches to address microbial (including *Legionella*), physical and chemical risks in various parts of the building water system, such as water management programs (WMPs), hazard analysis and critical control point (HACCP), and water safety plans (WSPs). This document also provides an overview of other strategies that primacy agencies, building water system operators, and building owners could consider when addressing threatening public health risks associated with a legionellosis outbreak.

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Although this document describes technologies for controlling *Legionella* in finished water, 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

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	The product of disinfectant residual concentration "C" and contact time "T" (C × T)
DBP	Disinfection byproduct
DBPR	Disinfectants and Disinfection Byproducts Rule
DPD	N,N-diethyl-p-phenylenediamine
EPA	United States Environmental Protection Agency
F	Fahrenheit
FIFRA	Federal Insecticide, Fungicide and Rodenticide Act
GWR	Ground Water Rule
HAA	Haloacetic acid
HAA5	Sum of the mass concentrations of five haloacetic acid species
HACCP	Hazard analysis and critical control points
HPC	Heterotrophic plate count
ICP/MS	Inductively coupled plasma/mass spectrometry
ICU	Intensive care unit
km	Kilometers
MCL	Maximum contaminant level
MF	Microfiltration
mg/L	Milligrams per liter
mJ/cm^2	Millijoule per square centimeter
mM	Millimolar
MRDL	Maximum residual disinfectant level
NDMA	*N*-nitrosodimethylamine
NF	Nanofiltration
OSHA	Occupational Safety and Health Administration
POE	Point-of-entry
POU	Point-of-use
ppm	Parts per million
PWS	Public water system
qPCR	Quantitative polymerase chain reaction
RO	Reverse osmosis
SDWA	Safe Drinking Water Act
SMCL	Secondary maximum contaminant level

spp.	All species within a genus
SWTR	Surface Water Treatment Rule
THM	Trihalomethane
TTHM	Total trihalomethane
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
WHO	World Health Organization
WMP	Water management programs
WSG	Water supply guidance
WSP	Water safety plan

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Preface

This draft document is a compilation of publicly available, peer-reviewed, technical literature that evaluates the effectiveness of technologies to control for *Legionella*. The United States Environmental Protection Agency (EPA) developed this document because the agency recognizes that *Legionella* is a public health threat. EPA also recognizes that many facility managers are choosing to install treatment systems to prevent or mitigate *Legionella* in their building's plumbing systems. The agency expects this document will help to further improve public health by helping the targeted audience make science-based, risk management decisions regarding treatment and control of *Legionella* in buildings. The EPA is not promoting or endorsing treatment technologies as a preferred means of *Legionella* control. Rather the agency seeks to provide decision makers with scientific information on the effectiveness of these technologies and the operational requirements. The target audience for this document includes, but is not limited to, primacy agencies, building water system operators, building owners and technology developers and vendors.

The intent of this document is to provide a summary of scientific information on *Legionella* control technologies that may be considered when assessing a particular building water system(s). The EPA did not evaluate individual study quality with the goal of making recommendations for or against the use of any of the technologies discussed in the document.

The scientific information presented in this draft 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 draft document also discusses water quality issues that could result when using the various approaches, and it summarizes operational conditions for each technology. It also discusses critical multi-barrier approaches for addressing microbial, physical and chemical risks in various parts of the building water system, such as water management programs (WMPs), hazard analysis and critical control point (HACCP), and water safety plans (WSPs). This document also provides an overview of other strategies that primacy agencies, building water system operators and building owners could consider when addressing a public health threat such as a legionellosis outbreak.

The EPA developed this draft document in collaboration with state co-regulators. *Legionella* subject matter experts at the Centers for Disease Control and Prevention (CDC) reviewed and provided feedback on portions of the draft document. All parties were invited to compile the peer-reviewed literature referenced in this document. The scientific information in this document spans from the 1970s to 2014 and is limited to peer-reviewed literature. 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 all building water systems. A determination of which strategy is best suited for a particular building water system is case-specific due in part to the complex and diverse nature of building water systems.

This document does not recommend the addition of treatment nor the installation of any of the technologies discussed herein, but rather provides technical information, based on the publicly

available, peer-reviewed literature, about technologies and other approaches for controlling *Legionella* and other microbial contaminants. In some facilities, risks associated with the building water system (including *Legionella*) may be addressed without the addition of 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, "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.

Executive Summary

[This is a placeholder. The Executive Summary will be drafted after comments from the public and expert peer review have been incorporated.]

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* in building finished drinking water systems (building water systems).[1] Throughout this document the term building water system refers to the pipe infrastructure inside a building used to deliver finished drinking 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). Discussions of *Legionella* control issues related to cooling towers are not within the scope of this document. The EPA developed this document in collaboration with state co-regulators. *Legionella* subject matter experts at the Centers for Disease Control (CDC) reviewed and provided feedback on portions of the draft document. All parties were invited to compile the peer-reviewed literature that is summarized and referenced in this document.

The agency expects this document will help to further improve public health by helping the primacy agencies,[2] building water system operators, building owners, technology developers and vendors make science-based risk management decisions regarding treatment and control of *Legionella* in buildings. The EPA is not promoting or endorsing treatment technologies as a preferred means of *Legionella* control in buildings. Rather, the agency seeks to provide decision makers with scientific information on the effectiveness of these technologies and the operational requirements. The EPA did not evaluate individual study quality or the body of evidence from available studies with the goal of making recommendations for or against the use of any of the technologies discussed in the document.

1.2 *Legionella*: Overview

1.2.1 General Information

The genus *Legionella* currently includes more than 50 bacterial species and approximately 70 distinct serogroups, many of which are considered pathogenic (DSMZ, 2014; LPSN, 2014; Pearce et al., 2012; Bartram et al., 2007; Fields et al., 2002). *Legionella 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 (any disease caused by *Legionella*), but it is likely that most *Legionellae* can cause human disease under the appropriate conditions (Borella

[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 State if they meet certain requirements.

et al., 2005; 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).

Legionellae are gram-negative, rod-shaped bacteria. 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 person-to-person contact, animal-to-person transmission, consumption of contaminated food, or ingestion of contaminated water. Though animals can be infected by *Legionella* and develop disease, they have not been identified as carriers of *Legionella*, nor has transmission from animals to humans been documented (Cunha, 2006; USEPA, 1999a).

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 and intensive care is common among Legionnaires' disease patients; inpatient costs are estimated at $433 million per year, with a case fatality rate of 5–30 percent (Collier et al., 2012). 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 any case that is confirmed by a laboratory is reported to CDC by state health departments (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; however, the actual number of hospitalized cases is estimated to be between 8,000 and 18,000 (CDC, 2013a; CDC, 2012; 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 2010, CDC reported that *Legionella* accounted for 19 of the 33 drinking water-related waterborne disease outbreaks in the United States, causing 72 illnesses and 8 deaths. Environmental conditions within building water systems were identified as the cause of 11 of the 19 *Legionella* outbreaks (CDC, 2013b).

Strains of *L. pneumophila* belonging to serogroup 1 are responsible for most legionellosis cases in the United States and Europe (Borella et al., 2005; 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).

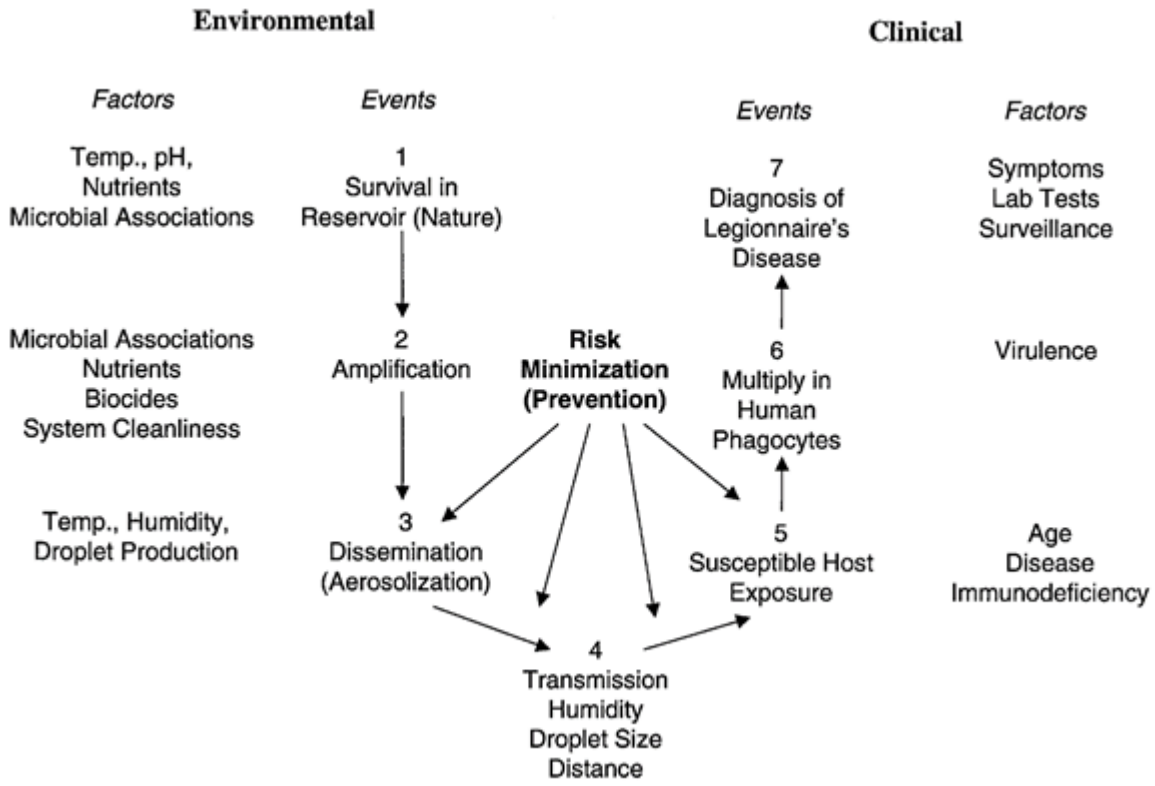
Although *L. pneumophila* causes most cases of Legionnaires' disease, other species can also cause the disease, particularly in hospital-acquired cases. Of the reported non-*L. pneumophila* infections, the most common causes of infection are *L. micdadei*, *L. bozemanii*, *L. dumoffii* and *L. longbeachae* (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 and drinking habits, existing lung conditions (e.g., asthma, chronic obstructive pulmonary disease),

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; Newton et al., 2010; Bartram et al., 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. Legionellosis 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). However, recent outbreaks have demonstrated that legionellosis infections are not limited to those environments.

Exhibit 1-1: *Legionella* transmission



Source: ASHRAE, 2000

Building water systems can be colonized with *Legionella* and transmit the bacteria through showerheads, faucets, whirlpool spas, respiratory therapy devices, ultrasonic mist machines, humidifiers, cooling towers, decorative fountains and industrial-use water (Haupt et al., 2012; Wallensten et al., 2010; Carducci et al., 2010; Edelstein, 2007; 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). Cases have also been linked to ice machines, windshield washer fluid

and birthing pools (Public Health England, 2014; Wallensten et al., 2010; 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).

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* species 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).

Legionella exhibit several properties that allow them to persist in extreme environmental conditions such as low and high temperatures, presence of disinfectants, low pH, low nutrients and high salinity (Health Canada, 2013; Borella et al., 2005; Kuchta et al., 1983; Fliermans et al., 1981). Ideal growth conditions are in warm water between 35 and 46 degrees Celsius (C) (95–114.8 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* species in contaminated aerosols (Heng et al., 1995). *Legionellae* are considered thermotolerant bacteria, able to withstand temperatures of 50 degrees C (122 degrees F) for several hours (Bartram et al., 2007). This characteristic allows *Legionella* species to occur frequently in heated water systems (Taylor et al., 2009). *Legionella* species can also survive at temperatures below 20 degrees C (68 degrees F) and even below freezing (Borella et al., 2005).

Legionella species 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. The association of *L. pneumophila* with many different microorganisms in aqueous environments has been widely demonstrated. Studies have shown the ability of *Legionella* to parasitize and multiply in several species of protozoa including amoebae, ciliated protozoa and slime mold (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* species 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 (Hoffman et al., 2014; Escoll et al., 2013; Richards et al., 2013; Bartram et al., 2007; Hwang et al., 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 (Hoffman et al., 2014).

Multiple studies suggest that protozoa play a major role in the transmission of *L. pneumophila* and subsequently, legionellosis. Some of the research indicates 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., 2005; Cirillo et al., 1999; Brieland et al., 1996). Infected amoebae may contain hundreds of *Legionella* cells, which, when released from the amoeba, 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.

Another survival mechanism of *Legionella* spp. is their ability to enter a viable but not culturable (VBNC) state. Bacteria in a VBNC state fail to grow on culture media, where they would normally grow, yet are still alive and could cause disease (Oliver, 2010). Numerous chemical and environmental factors have been reported to induce a VBNC state, including nutrient starvation, extreme temperatures, high salt concentrations, low oxygen concentration, heavy metals and chemical treatment (including water disinfection) (Ducret et al., 2014; Alleron 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 System and Building Water System

Building water systems have been identified as sources of *Legionella* infection (Stout et al., 1992; Muder et al., 1986), particularly through exposure via showers and hot water systems. Within healthcare facilities such as hospitals and nursing homes drinking water is the most common source of exposure (Lin et al., 2011a). Exposure to *Legionella* has also been associated with other types of building water 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).

L. pneumophila has been found in the biofilms of water mains in distribution systems, although proliferation has not been shown (Armon et al., 1997; States et al., 1990). *Legionella* spp. are known to occur in finished water from water treatment plants and therefore, drinking water is known to be a source of *Legionella* found in building water systems (Donohue et al., 2014; Schaechter et al., 1998). Section 1.2.3 discusses optimal conditions for *Legionella* growth in the distribution system.

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

- Donohue et al. (2014) used two quantitative polymerase chain reaction (qPCR)[3] 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.

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

- Wadowsky et al. (1985) found that naturally occurring *L. pneumophila* multiplied at a temperature between 25 and 37 degrees C, at pH levels of 5.5 to 9.2, and at concentrations of dissolved oxygen of 6.0 to 6.7 mg/L.

- 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 1 of the 5 homes. *Legionellae* 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 building water systems.

- Tobin et al. (1981b) conducted a survey of 31 building water systems in 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 building water 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.

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 inactivation of *Giardia* and 4-log inactivation of viruses), then *Legionella* risks will also be controlled. In addition, the Revised Total Coliform Rule and the Ground Water Rule have treatment technique requirements that address bacteria, which provide some control of *Legionella*. All of these rules apply to public water systems (PWSs).

Building water systems may or may not be subject to federal drinking water regulations under 40 CFR Part 141. States and/or local governments may have drinking water standards for such systems even if federal regulations do not apply. To ensure adequate public health protection, federal and state oversight may be needed since adding certain technologies in a building water system could impact the chemical and microbial quality of the water within the system. The EPA issued guidance that primacy agencies may use as they make regulatory implication decisions (USEPA, 1976, USEPA, 1990).

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

Building owners who are considering adding treatment to their building water systems may wish to consult with their water supplier (i.e., PWS) to better understand any potential water quality issues before making treatment related decisions. If a decision to add treatment to the building water system seems likely, EPA advises building owners to consult with their primacy agency for any specific requirements that may apply before they add any treatment.

2 Multi-Barrier Approaches and Technologies to Control *Legionella*

2.1 Overview of Current State of Knowledge

The following sections of this document describe multi-barrier approaches and technologies for controlling *Legionella* in building water systems. The information presented is based on the references reviewed during the preparation of this document. Section 2.2 introduces multi-barrier approaches as a framework for identifying and prioritizing hazards within a particular building water 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 potential exposure to *Legionella* in building water 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 drinking water requirements. Applicability of such requirements to a building water system would need to be determined by the building water system operator in consultation with the primacy agency and/or water supplier.

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 building water 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, which could provide opportunities for bacteria to grow. *Legionella* bacteria can be found in biofilms or in stagnant sections of the plumbing system. The effectiveness of a technology against *Legionella* in biofilm or *Legionella* ingested by amoebae is often cited as a concern.

The maintenance of 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 building water system (e.g., sloughing off of biofilm material containing *Legionella*) or enters a building water system through the PWS distribution system. Ozone and UV disinfection do not produce a disinfectant residual. Therefore, water treated with these methods, in some cases, may be

susceptible to subsequent contamination. For these reasons, more than one type of treatment or control measure may be necessary to inhibit *Legionella* growth in a building water system (Department of Veterans Affairs, 2014). The use of multi-barrier 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 building water 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 have an impact on the effectiveness of all the treatment technologies discussed, 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 to faster reaction 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 significantly impact the effectiveness of chlorine, monochloramine and copper and silver ions, but it will have less of an impact on the effectiveness of chlorine dioxide. 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 building inhabitants from exposure to *Legionella* have resulted in outbreaks (CDC, 2013b). 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 Disinfection Byproduct Rule (DBPR) requires PWSs using chlorine, monochloramine and chlorine dioxide to maintain disinfection byproduct (DBP) concentrations below levels that can cause negative human health implications (USEPA, 1998; Rohr et al., 1999; States et al., 1998). These water quality issues are discussed in Section 2.3.

Unless a legionellosis outbreak occurs, the decision to employ additional treatment is often difficult for building owners. Some building owners choose to install supplemental disinfection treatment systems as a preventative measure based on economic, insurance or marketing reasons. The detection of *Legionella* bacteria in finished 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). However, because of the ubiquitous nature of environmental *Legionella*, a robust response to every positive test result is likely unnecessary and could be both costly and damaging to the building infrastructure. Outbreaks of legionellosis have occurred when this metric was applied. In some instances, risks associated with the building water system (including *Legionella*) can be addressed by taking measures other than the addition of treatment after careful analysis of the particular conditions of the building water system. Thus, decision makers may want to consider the specific conditions of a building water system to better inform decisions made in response to detection of *Legionella*. Multi-barrier approaches commonly

include consideration of parameters such as the building water system layout, water processes such as heating and water softening, methods of transmission such as showers and spas, and the risk level of the potentially exposed population based on age and immune status.

2.2 Multi-Barrier Approaches

2.2.1 Background

Multi-barrier approaches refer to programs that systematically apply risk management principles to reduce biological (including *Legionella*), chemical and physical risks associated with building water systems. Different names are used throughout the literature to describe multi-barrier approaches. Some examples of multi-barrier 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 by The Pillsbury Company in coordination with the National Aeronautic and Space Administration and the U.S. Army Laboratories. It was created to ensure the safety of food from microbiological hazards for astronauts working in space (Mortimore and Wallace, 2001). Beginning in the mid-1970s, HACCP principles were applied to the food industry as a preventative approach for addressing biological, chemical and physical hazards. 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). After seeing the success of HACCP in the food industry, water utilities began to implement the HACCP approach. The process for using HACCP in a water system was originally described within a food journal, *Food Control*, in 1994 (Havelaar, 1994).

HACCP can be viewed as a continuous multi-barrier approach for protecting finished water and building water systems from hazards that may occur. While many water systems use some aspects of the HACCP approach, implementing a full HACCP program that evaluates an entire system in detail ensures the highest level of public health protection (Deere and Davison, 1998).

WSPs are also considered a comprehensive risk-management approach; WSPs use multiple barriers to ensure public health protection from the source to the tap (WHO, 2011). The use of HACCP in the water industry was the basis for the development of WSPs by the WHO (Figueras and Borrego, 2010; WHO, 2005).

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

The application of any multi-barrier approaches, such as WMP, HACCP or WSPs can be beneficial for water systems and building water systems in protecting 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 elements

elements, see the Appendix of this document. Slight variations can be observed in the elements or steps described by each approach. The EPA does not make any specific recommendation regarding the use of any particular approach. The EPA advises building water system operators and owners to determine which approaches may be more suitable to their specific needs or whether a combination of approaches is appropriate.

2.2.2 Applications of Multi-Barrier Approaches

Water system managers have found success in implementing multi-barrier approaches such as WMP, HACCP and WSP, similar to the successes seen in the food industry for many years. In 1999, Brisbane, Australia, employed HACCP as a means of protecting the water treatment process, storage and distribution system (Gray and Morain, 2000). A system in Melbourne, Australia, implemented HACCP in 1999 and improved outcomes including streamlined work procedures, a net decrease in customer complaints, and a better understanding of the quality issues (Mullenger et al., 2002). Five full-scale HACCP applications in Australian water distribution systems resulted in reductions in customer complaints and water quality incidents. Other improvements attributed to HACCP were noted in work processes, documentation and recordkeeping, and the system's capability to demonstrate due diligence. Pilot-scale applications in U.S. distribution systems showed that HACCP was feasible and practical, but the time and resource requirements for implementing the plans were greater than expected (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). 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 HACCP (Gunnarsdóttir and Gissurarson, 2008).

Implementing multi-barrier risk management concepts for building water systems has also been shown to be successful. The Occupational Safety and Health Administration (OSHA) recognizes the importance of having controls for building water systems in place, as under the right conditions any water source can be a source of disease and illness (OSHA, 1999). ASHRAE also recognizes the importance of risk management for building water systems in its Standard 188, *Legionellosis: Risk Management for Building Water Systems* (ASHRAE, 2015). NSF International is developing a draft standard based on application of HACCP to building water systems for *Legionella* control. In addition to applying multi-barrier risk management concepts to existing building water systems, building designers can also use these concepts in the design phase for new building water systems to help reduce and control hazards (Krageschmidt et al., 2014).

Multi-barrier approaches have proven to be effective for controlling the growth of significant pathogens in building water systems (Gillilland et al., 2014), as documented in the following case studies:

- In 2004, a university clinic in Germany adopted the WSP concept based on HACCP. 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 (hospital-acquired) Legionnaires' disease since implementation (Dyck et al., 2007).

- In Minnesota, the Mayo Clinic used HACCP principles to build a water management program for its multi-campus healthcare facilities. During implementation of HACCP the clinic found distribution piping design issues and determined that additional hazard controls were needed. The water management program improved the awareness of water quality issues (Krageschmidt et al., 2014).

- Evaluations of outbreaks of Legionnaires' disease have shown system deficiencies to be contributing factors to outbreaks (CDC, 2013b). The implementation of HACCP plans or WSPs may identify and help to correct these deficiencies.

In addition to applying multi-barrier risk management concepts to existing building water systems, building designers can also use these concepts in the design phase for new building water systems to help reduce and control hazards (Krageschmidt et al., 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 which can be a source of *Legionella*; the Veterans Administration has concluded that they should not be included in healthcare interior designs (Department of Veterans Affairs, 2012).

Addition of treatment as part of a multi-barrier approach into a building water system's operation and maintenance program could have regulatory implications. The EPA advises building owners who are considering adding treatment to consult with their water supplier and primacy agency for any specific considerations or requirements that may apply.

2.2.3 Environmental Testing

Environmental testing involves collecting water samples from the building water 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 in the context of an outbreak investigation in order to determine the source and stop transmission or as part of a multi-barrier *Legionella* prevention plan such as a WMP, HACCP or WSP (ASHRAE, 2015; Sidari et al., 2014; Kozak et al., 2013).

Using *Legionella* test results as a measure of risk for disease transmission is problematic due to many knowledge gaps, including but not limited to, infectious dose, efficiency of aerosol-generating devices, susceptibility of potential hosts, and virulence of the strain. While detection of *Legionella* in a building water system may indicate conditions conducive to *Legionella* persistence, it is also clear from worldwide studies that the strains of *Legionella* most often detected during routine environmental testing are rarely the strains that cause disease (Kozak-Muiznieks et al., 2014; Euser et al., 2013; Harrison et al., 2009, Kozak et al., 2009; Doleans et al., 2004). 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 (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).

Guidelines on routine environmental testing for *Legionella* vary among different agencies, including the Veterans Health Administration (VHA), CDC, and WHO (Barker et al., 2015). VHA recommends routine environmental testing for *Legionella* in VHA facilities (VHA, 2014). 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 (Bartram et al., 2007; Sehulster and Chinn, 2003). Despite the limitations of environmental monitoring, WHO continues to recommend using *Legionella* testing as one way to validate a WSP (Bartram et al., 2007). Similarly, a WMP or HACCP approach for protecting a building water system might involve routinely monitoring water temperature, disinfectant residual levels, and the functioning of any other treatment system, leaving the more complicated testing for *Legionella* for validation of the plan being used. 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). Further, the time it takes to receive results limits the utility of testing.

- Wide fluctuations occur in *Legionella* testing results from the same tap on a daily basis and from the same water sample between laboratories (Lucas et al., 2011).

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

If a decision is made to conduct routine environmental testing for *Legionella* as part of a multi-barrier approach, a building-specific sampling plan should 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 (Krageschmidt et al., 2014). 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 (Calomoris and Christman, 1998). Chlorine is a powerful oxidant that effectively inactivates a large variety of microbial waterborne pathogens, including those that can cause typhoid fever, dysentery, cholera and Legionnaires' disease.

Chlorine is added to drinking water as elemental chlorine (chlorine gas), sodium hypochlorite solution or dry calcium hypochlorite. Chlorine as sodium hypochlorite is the form of disinfectant most often applied in buildings (Rosenblatt and McCoy, 2014). 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. 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 it must have adequate time to react (Calomoris and Christman, 1998). 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 building water 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 as a primary disinfectant of drinking water in Jersey City, New Jersey, in 1908. Chlorine is widely credited with virtually eliminating outbreaks of waterborne disease in the United States and other developed countries (Calomoris and Christman, 1998). The use of chlorine to control microbes has the lowest production and operating costs of any disinfectant, as well as the longest history for large continuous disinfection operations. 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. Lin 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.
- The effectiveness of chlorine increased with temperature, although chlorine residual decay also increased.
- The association of *Legionella* with protozoa required much higher doses of chlorine for inactivation. Lin et al. (2002) noted that this association with protozoa may explain why chlorine can suppress *Legionella* in water systems but cannot usually prevent regrowth of *Legionella*.

The laboratory studies that follow examined the effectiveness of chlorine in inactivating *Legionella* under a range of pH, temperature and chlorine residual levels. Results showed a wide range of CT values needed for all inactivation levels.

- 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 ranges of pH and temperature conditions evaluated are shown in Exhibit 2-1. Results show that lower CT is required for higher temperature and lower pH. 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.

Exhibit 2-1: Kuchta et al. (1983) findings on CT values (min-mg/L) for 2-log (99 percent) reduction of *L. pneumophila* using chlorine

Temperature in degrees C (in degrees F)	pH 6.0	pH 7.0	pH 7.6
4 (39.2)			6–9
21 (69.8)	0.5	1–6	4
32 (89.6)		3.2	<3

Source: Kuchta et al. (1983)

- 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. Results are presented as CT (min-mg/L) values. The observed CT values for 2-log (99 percent) reduction of *L. pneumophila* are shown in Exhibit 2-2. These CT values were at least an order of magnitude higher than those reported by Kuchta et al. (1983). 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*.

Exhibit 2-2: Jacangelo et al. (2002) findings on CT values (min-mg/L) for 2-log (99 percent) reduction of *L. pneumophila* using chlorine

Temperature in degrees C (in degrees F)	pH 6.0	pH 7.0	pH 8.0
5 (41)	>50 to >320	50 to 250	250 to >1,000
15 (59)	100 to >320	60 to >320	25 to >710
25 (77)	40 to 500	100 to 160	130 to 250

Source: Jacangelo et al. (2002)

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.

- Muraca et al. (1987) compared chlorine, heat, ozone and UV for inactivating *Legionella* in a model building water system. A suspension of *Legionella* was added to the system and allowed to circulate. Chlorine disinfection consisted of maintaining a residual concentration between 4 and 6 mg/L by multiple additions of chlorine. Chlorine experiments were conducted at 25, 43 and 45 degrees C (77, 109.4 and 113 degrees F, respectively). Continuous chlorination at a dose of 4 to 6 mg/L resulted in a 5- to 6-log 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 23 degrees C (73.4 degrees F). Due to thermal decomposition of chlorine residual, approximately 120 percent more chlorine was needed to maintain a residual of 4–6 mg/L at 43 degrees C (109.4 degrees F). 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.

- 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 this treatment was very effective at maintaining viable bacteria, including *Legionella*, at low levels. 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.

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

- 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 of 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 reduction (99.9 percent) at contact times of ≥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. Both 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.

- Dupuy et al. (2011) also investigated the interaction of amoebae and *Legionella*. 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 residual 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 inactivation (99.9 percent) 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).

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

- In a 1994 paper, de Beer et al. studied the degree to which chlorine penetrates a biofilm based on bulk concentration. For this study, biofilms consisting of *Pseudomonas aeruginosa* and *Klebsiella 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 microprofiles 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 microprofiles 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.

- Loret et al. (2005) expanded on the de Beer et al. (1994) study by using a simulated distribution system consisting of pipe loops to compare disinfectants for *Legionella* control in biofilms in building water 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 stagnant 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, or colony-forming units per liter) 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 so-called 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). Ozone was found to be effective for controlling the planktonic and biofilm populations within the pipe loops but was ineffective within dead end sections. Monochloramine was found to be ineffective for the amoebae and in the biofilm. 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.

- 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 *Legionellae* were able to survive and persist at free chlorine concentrations of 0.5 mg/L.

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 chlorination) from cold water piping, mixed cold and hot piping, and hot water piping. Shock hyperchlorination was described as an applied concentration of 20–50 parts per million (ppm), and continuous chlorination was described as a continuously applied concentration of 0.5–1.0 ppm. The study found a significant association between the presence of *Legionella* in the building drinking water 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 eradicate *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 building water 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 organic material in the water to form DBPs in systems with areas of low flow or stagnant waters. 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 distribution system of pipe loops, Loret et al. (2005) found trihalomethane (THM) levels >100 micrograms per liter (µg/L), bromate levels >10 µg/L, and chlorite levels >0.2 mg/L with an applied chlorine dose of 2 mg/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.

Continuous chlorination at high levels in building water 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. 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 (Sarver et al., 2011). In a study by Grosserode et al. (1993), leaks first appeared in the copper pipes of a water distribution 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, buffering capacity of the water, concentration of organic matter, and the number and types of microorganisms in the water system (in biofilms and free-living). Sidari et al. (2014) reported that the typical concentration of supplemental chlorine is 2–4 mg/L as free residual chlorine. 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 ≥8. However, free chlorine is degraded rapidly at elevated water temperatures, which is a concern for hot water chlorination (Health Protection Surveillance Centre, 2009).

Operational Considerations

To help ensure its effectiveness, standard industry practices recommend how sodium hypochlorite should be stored and handled to minimize decomposition of the product (GLUMRBSPPHEM 2012). It 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. 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. The Chemical Facility Anti-Terrorism Standards include information on standard practices for storage and handling of chlorine gas (Department of Homeland Security, 2015). 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.

Monitoring Frequency and Location

The Surface Water Treatment Rule (SWTR) (USEPA, 1989a) requires that all PWSs using chlorine and using surface water or ground water under the direct influence of surface water monitor for the presence of the residual disinfectant in the distribution system or at the point-of-entry (POE) to the distribution system. The disinfectant level must be >0.2 mg/L at the POE and detectable within the distribution system.

The Stage 1 Disinfectants and Disinfection Byproducts Rule (Stage 1 DBPR) requires PWSs that use chlorine to maintain a maximum residual disinfectant level (MRDL) as running annual average less than 4.0 mg/L (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. All 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

Operating 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 building water system (HSE, 2014; Rosenblatt and McCoy, 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 building finished water 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 for residual disinfection 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. 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).

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. 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 (Kirk-Othmer, 1979) 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 DBPR (Seidel et al., 2005; USEPA, 2005a).

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*.

- 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 *L. pneumophila* with a CT range between 16.14±3.07 min-mg/L and 64.88±19.07 min-mg/L. The study also found that temperature, pH and initial bacterial concentration affected the ability of monochloramine to inactivate *Legionella*. Increasing the temperature had a positive effect on monochloramine activity but a negative effect on the contact time required to inactivate 99.9 percent of the *Legionella*. Increasing the pH had a negative effect on monochloramine activity but a positive effect on the contact time required to inactivate 99.9 percent of the *Legionella* (Jakubek et al., 2013).

- 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 $\geq$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 (Jacangelo et al., 2002).

- 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 *Legionella* was inactivated (i.e., 2-log removal). Using the 1.5 mg/L concentration of monochloramine, 99.9 percent of *Legionella* was inactivated (i.e., 3-log removal) at 60 and 180 minutes contact time (Donlan et al., 2002).

- A study conducted by Cunliffe (1990) evaluated *Legionella* 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 *Legionella* was more sensitive to monochloramine than *E. coli* (Cunliffe, 1990).

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*.

Several 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. *Legionella* was only detected during the 14-month sampling event in bulk water and at lower water ages for chloraminated systems.

- Dupuy et al. (2011) evaluated the inactivation of both free and intracellular *L. pneumophila* (co-occurring with *Acanthamoeba*) using different disinfectants. The 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*.

- 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).

- Türetgen (2004) conducted a study of the efficacy of monochloramine and chlorine against biofilms using different contact times and different concentrations on a full-scale and model system cooling tower. Monochloramine was found to be significantly more effective against cooling tower biofilms than free chlorine. In both systems, a 3-log (99.9 percent) reduction of heterotrophic biofilm bacteria was achieved using a monochloramine concentration of 1.5 ppm for a contact time of about 35 minutes. Monochloramine is unaffected by the elevated pH levels within the cooling towers, unlike chlorine. To completely remove biofilms from a cooling tower additional treatment would be needed, such as physical cleaning (Türetgen, 2004).

- 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 *Legionella* levels within a biofilm reactor. They found monochloramine to be more effective than chlorine in identical conditions for *Legionella* 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 *Legionella* control in building water systems receiving water from a distribution system where the treatment plant converted from chlorine to monochloramine. Several studies evaluated the addition of monochloramine for the treatment of building water systems. Other studies compared *Legionella* control in water systems using different disinfection methods.

- Baron et al. (2014) 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, and 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* were observed. Trends for *Legionella* counts varied but did not show an increase. 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.

- Whiley et al. (2014) measured *Legionella* spp., *L. pneumophila* and mycobacterium avium complex in two drinking water distribution systems: DS1, 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. 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 the distribution system 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).

- Duda et al. (2014) observed a significant reduction in *Legionella* at distal sites after a monochloramine generation system was installed in a hospital hot water system. The observations were based on 29 months of monitoring data including a five-month baseline period and 24 months' data following installation.

- A hospital in Italy added monochloramine treatment into 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, 13.3 percent of samples were positive for *Legionella*. The authors concluded that based on this full-scale 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 below 10^2 CFU/L.

- Weintraub et al. (2008) evaluated water and biofilm samples from 53 buildings in San Francisco before and after conversion 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 when controlling for building and water characteristics (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 drinking water system 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 water systems after the wholesale PWS had converted from chlorine to monochloramine for residual disinfection treatment. *Legionella* colonization of building water 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 (Moore et al., 2006).

- 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 responded (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) used monochloramine for disinfection of the municipal water supply. 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; confidence interval (95 percent): 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 at al., 2002; Lin et al., 2000a).

2.3.2.3 Potential Water Quality Issues

Potential water quality issues with monochloramine include corrosion, formation of DBPs, and nitrification. Monochloramine can impact kidney dialysis and should be removed from the dialysate water. Monochloramine should be removed from water used for fish tanks due to detrimental effects.

An unintended consequence of using monochloramine is 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) reported that chloramine can attack rubber and plastic components in a water system and that 23 percent of utilities surveyed experienced an increase in degradation of rubber materials after chloramine disinfection was implemented. Water temperature, pH and disinfectant concentration also affect corrosion rates. Monochloramine can react with pipe scale differently than other disinfectants, resulting in lead leaching in system materials containing lead (Edwards and Dudi, 2004). Corrosion control and maintenance of building water 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 building water system and to better understand the effects of these interactions on the efficacy of pathogen inactivation (Rhoads et al., 2014).

Another unintended consequence of monochloramine disinfection is its ability to react with organics in the water to form DBPs. Although chloramination significantly reduces some DBPs, such as THM and haloacetic acids (HAA), 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, 2014b) on EPA's website.

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.

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*, building water 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 (Pryor et al., 2004). Building water system 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.

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 above generally support maintaining a chloramine residual in the building water 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, building water system maintenance such as appropriate pH, 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 5 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 that all PWSs using monochloramine and using surface water or ground water under the direct influence of surface water monitor for the presence of a disinfectant residual in the distribution system and at the POE to the distribution system. The disinfectant level must be at least 0.2 mg/L at POE and detectable in at least 95 percent of samples collected within the distribution system.

Stage 1 DBPR also requires PWSs that use monochloramine to maintain an MRDL 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. All of 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). The 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, 2014a).

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 building water system (HSE, 2014; Rosenblatt and McCoy, 2014).

Systems using monochloramine as a residual disinfectant periodically use free chlorine to eliminate biological growth that may have occurred in the distribution system or on equipment (AWWA, 2013; Lin et al., 2000b).

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

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). It is a very effective disinfectant (when used correctly) at inactivating bacterial, viral and protozoan pathogens and has a high oxidation potential (USEPA, 1999b). Its use as a biocide can be maintained over a wider pH range than chlorine or CSI (Lin et al., 2011b).

Chlorine dioxide was first used as a disinfectant in the early 1900s at a spa in Belgium, and 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, while in Europe, it 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 total trihalomethanes (TTHMs) (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 building 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).

Use of chlorine dioxide in PWSs is regulated by the DBPR. 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 DBPR sets a maximum contaminant level (MCL) of 1.0 mg/L for chlorite.

2.3.3.1 Characterization of Effectiveness against *Legionella*

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, it is never shipped (USEPA, 1999b). Water

treatment chemicals must meet the appropriate ANSI/AWWA standards or NSF/ANSI Standard 60 (GLUMRBSPPHEM 2012).

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 (i.e., providing at least a 3-log (99.9 percent) reduction of the bacterial population at study conditions) free *L. pneumophila* than co-cultured *L. pneumophila*. 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 building water 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, and 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 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.

Chlorine dioxide disinfection systems have been installed in many 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 multi-barrier 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 *Legionella* contamination in three hospital hot water systems over a three-year period compared to the untreated systems. A dosage rate of 0.50–0.70 mg/L chlorine dioxide was applied to the hot water systems, with the goal of maintaining a minimum concentration of 0.30 mg/L at distal sites (i.e., sink taps, tubs and showers located at distant points in the building water system. 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 building water systems 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. Electric boilers and POU filters had better performance than chlorine dioxide.[4] The authors suggested implementing chlorine dioxide and electric boilers in parallel to control *Legionella*.

- 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. 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

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

measures were unsuccessful. Chlorine dioxide was injected into the cold water main at a dosage rate of 0.5–0.7 mg/L to control *Legionella* and maintain chlorite levels below the MCL at both hot and cold water taps. 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. *Legionella* was eradicated (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. 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.

2.3.3.2 Potential Water Quality Issues

Chlorine dioxide does not form the high levels of chlorinated DBPs that chlorination does (Gates et al., 2009). Chlorite and chlorate are the most prominent byproducts of chlorine dioxide (Gates et al., 2009). 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). In an Italian hospital where chlorine dioxide was used to control *Legionella* 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.

Water treatment utilities use chlorine dioxide for taste and odor control; however, various odors were reported when chloride dioxide residuals exceeded 0.05 mg/L in the winter or 0.15 mg/L in the summer (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 and Hoehn, 1991). The taste and odor threshold for chlorine dioxide in water has been reported to be as low as 0.2 mg/L (Roche and Benanou, 2007).

Chlorine dioxide is considered less corrosive than chlorine (Lin et al., 2011b). Some reports suggest that chlorine dioxide can cause damages to polyethylene pipes (Chord et al., 2011; Yu et al., 2011); however, information on other types of pipes is sparse (Gates et al., 2009).

2.3.3.3 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, the extent of biofilm on pipe surfaces, pipe diameter and length, complexity of the building water system, treatment goals (e.g., *Legionella* control), and the water turnover rate. For example, corrosion of galvanized piping can increase the water's disinfectant demand and reduce the residual chlorine dioxide level (Lin et al., 2011b). One study (Zhang et al., 2009) reported the chlorine dioxide demand of the building water 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 may want to 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 in December 2006, 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).

- Marchesi et al. (2013) reported that some samples associated with the chlorine dioxide treatment systems had chlorite levels higher than the Italian regulatory limit of 0.7 mg/L. Such exceedances would occur when the chlorine dioxide residual was >0.30 mg/L at distal taps. Because successful treatment performance (stated above) was based on maintaining a chlorine dioxide residual $\geq$0.30 mg/L at distal taps, this case highlights the importance of balancing disinfection needs with minimizing DBP formation.

- The lack of proper monitoring for a chlorine dioxide treatment system for drinking water was noted at a New York heath care facility after it experienced a *Legionella* outbreak in 2010 (CDC, 2013b). 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*. 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.

- Sidari et al. (2004) reported differences in the time required to eradicate *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, which may explain why 20 months of treatment was required to eradicate (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 system.

Monitoring Frequency and Location

The SWTR (USEPA, 1989a) requires that all PWSs using chlorine dioxide monitor the level of residual disinfectant present in the water supply. The Stage 1 DBPR also requires that these PWSs 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 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 DBPR.

The Stage 1 DBPR and Stage 2 DBPR require that all PWSs using chlorine dioxide monitor chlorite for compliance with the MCL (USEPA, 2006c). Chlorite must be monitored daily at the entry point to the distribution system, 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 Table Footnote 8 in 40 CFR 141.131(b)).

Maintenance Needs

Operating and maintenance practices for chlorine dioxide disinfection systems include maintenance of a disinfectant residual, regular system cleaning and flushing, inspections, and water quality monitoring. A newly constructed or rehabilitated piping system should be cleaned and flushed prior to initial disinfection (GLUMRBSPPHEM, 2012). Routine flushing and water quality monitoring are recommended to assure that adequate disinfectant levels are maintained throughout the building water system (HSE, 2014; Rosenblatt and McCoy, 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 earliest reports of CSI's antibacterial properties were published in the mid-1970s (Spadaro et al., 1974; Berger et al., 1976). The earliest combined use of copper and silver ions as water treatment focused on the disinfection of swimming pools (Yahya et al., 1989) as an alternative to using high levels of chlorine. A 1994 report on the use of CSI treatment was the first to address the efficacy of this treatment for controlling *Legionella* in hospital water systems (Liu et al., 1994). 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 eradicating *Legionella* from hospitals worldwide.

2.3.4.2 Characterization of Treatment Technology Effectiveness against *Legionella*

Case studies constitute the majority of the published reports on the efficacy of CSI in controlling *Legionella* in building water systems (Chen, 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 building water system and CSI was initiated in an attempt at *Legionella* control. Many of the reviewed laboratory studies indicate that copper and silver ions can reduce the cultivability of *Legionella* and 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.

- Lin et al. (1996) and Landeen et al. (1989) indicate that copper ions (at 0.4 mg/L) and silver ions (at 0.04 mg/L) can effectively reduce the cultivability of *Legionella* bacteria.

A 3- to 4-log (99.9 to 99.99 percent) reduction of culturable *Legionella* bacteria at these ion concentrations is reported to occur at pH 7.0–7.3, with exposure times reported to be <1 hour to 24 hours (Lin et al., 2002; Lin et al., 1996 and Landeen et al., 1989).

- Hwang et al. (2007) showed that *Legionella* bacteria that are ingested by amoebae (in biofilms along piping walls) are protected from inactivation by copper and silver ions; a concentration of copper and silver that would normally result in a 7-log reduction of planktonic *Legionella* in 30 minutes would not similarly affect *Legionella* bacteria inside an amoeba, where they can survive for many days.

- 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.

- Kusnetsov et al. (2001) reported a 100-fold decrease in culturable *Legionella* from biofilm samples after CSI treatment was employed.

- Rohr (1999) indicated an initial impact on *Legionella* occurrence, 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*.

- Mòdol et al. (2007) described how a large hospital experienced success in decreasing the number of positive *Legionella* samples after initiating CSI, only to see the number of positive samples increase from 20 percent to 65 percent during two months when the treatment system was under repair.

- Blanc et al. (2005) reported that the addition of copper and silver ions alone had no impact on the number of *Legionella*-positive water and biofilm samples in a large hospital.

- 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.

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, and 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 tolerant of copper and silver at the levels employed in CSI treatment has been noted (Rohr et al., 1999). 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)) that is 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 *Legionella* 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. Investigations have shown that test systems that exposed galvanized and mild steel (i.e., carbon steel) coupons to CSI resulted in corrosion (Loret et al., 2005). The authors noted that copper deposition resulted in extensive pitting in ferrous materials via localized galvanic corrosion events. Copper coupons in the same system were covered with copper deposits at pH 7.6. Some evaluation of deposition, pitting and corrosion of copper piping in a system using CSI was presented by Boffardi and Hannigan (2013). Both the presence of additional copper ions and the pre-existing water conditions appeared to contribute to Type III pitting corrosion. This type of 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 (Boffardi and Hannigan, 2013; 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.

Materials compatibility and water quality will dictate the severity of corrosion, and awareness of the types of materials and water chemistry in a building water system is critical to maintaining system integrity.

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 building water 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; no other causative factors have been

identified. Ingesting high levels of silver can also lead to a skin discoloration condition called "argyria" (Drake and Hazelwood, 2005; WHO, 1996; 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 building water 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*. These studies showed that *Legionella* are as much as 10-fold more sensitive to copper than *Pseudomonas*, *Stenotrophomonas* and *Acinetobacter*, but that *Legionella* are less sensitive to silver than *Pseudomonas* and *Stenotrophomonas* (Huang et al., 2008; Hwang et al., 2007). Copper and silver ions appear to act synergistically (the total effect is greater than the sum of the individual effects) toward *Legionella* (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 building water system (Kusnetsov et al., 2001).

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

Several physicochemical parameters that could impact treatment effectiveness are discussed in more detail below.

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). 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). It has also been reported that 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).

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 *Legionella* 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 a pH of 7, exposure to 0.4 mg/L of copper resulted in a 4-log (99.99 percent) reduction of culturable *Legionella* in one hour in a controlled laboratory study (Lin et al., 2002); however, at a pH of 9, there was no appreciable decrease in culturable *Legionella* over the same period of time with the same copper exposure. 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.

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 their 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.[5] 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.

Operational monitoring of copper is generally conducted weekly at a variety of locations throughout the building water system to monitor for process changes in copper concentration, high copper concentrations that may be indicative of improper application, and no detectable copper. Handheld colorimeters and reagents are available for monitoring copper in the field but

[5] 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."

laboratory analysis is needed to confirm field measurements (Sidari et al., 2014). These wet chemical tests have practical limits on detection when near the lower limit of detection (0.04 mg/L). These field methods are not approved for compliance monitoring.

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 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, 2006e). 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 water systems in the United States and Canada with UV installations treating flows >350 gallons per minute (Wright et al., 2012).

UV reactor validation helps to define the operational conditions under which the pathogens of concern are inactivated. 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. This bioassay helps determine the dose required for full-scale testing using the surrogate. 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. The EPA has developed guidance for validation of UV reactors (USEPA, 2006e). Independent organizations have used this EPA guidance to develop their own validation approaches. There are also several validation standards for UV reactors from organizations based in Austria (Österreichisches Normungsinstitut – ÖNORM) and Germany (Deutsche Vereinigung des Gas- und Wasserfaches – DVGW) that are widely accepted and use a benchmark UV dose of 40 millijoules per square centimeter (mJ/cm^2) (GLUMRBSPPHEM, 2012).

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. For applications related to *Legionella* control in buildings and other moderately sized facilities, reactors using the setpoint approach will likely be installed due to the ease of operations and control.

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 has been shown to be effective at decreasing and, in some cases, eliminating *Legionella* from facility piping.
- UV is only effective at inactivating *Legionella* in the water that flows through the UV reactor. For existing facilities with *Legionella* that is 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.

Relatively low UV doses appear to inactivate *L. pneumophila* (Exhibit 2-3). A dose of 1 mJ/cm^2 was found adequate to achieve 99 percent (2-log) reduction in six different *Legionella* spp. using irradiation times from 33 to 63 minutes depending on the species (Gilpin et al., 1985). A dose of 30 mJ/cm^2 achieved 99.999 percent (5-log) reduction in 20 minutes in a model building water system (Muraca et al., 1987).

Usually, there are limited opportunities for exposure to light for water treated and held in building water systems. However, if there is a significant opportunity for light repair (repair of UV-induced DNA damage using photoreactivating 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 *Legionella*, subsequent exposure to fluorescent light for one hour resulted in only a 68 percent (0.5-log) reduction following initial inactivation by low pressure UV lamps and only 60 percent (0.4-log) reduction following inactivation by medium pressure

UV lamps (Oguma et al., 2004). Similar significant light-repair of *Legionella* has been observed by others (Knudson, 1985).

Exhibit 2-3: 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
ATCC43660	LP	3.1	5.0	6.9	9.4	Wilson et al., 1992[1]

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.
[1] As reported by Wright et al. 2012.

Given the sensitivity of *Legionella* to UV disinfection, a well-maintained UV disinfection system can be effective at significantly decreasing the presence of *Legionella* in building water systems to less than 10 CFU/mL (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 disinfection may not be effective in pipe systems that have been colonized by bacteria. One study found no statistical difference in showers treated with UV and those not treated. However, Liu et al. (1995) showed that when the lines were disinfected, the UV treated showers remained *Legionella*-free for a month, while the untreated showers were recolonized by *Legionella* within a week.

Fouling of the UV lamps was found to decrease effectiveness of the UV treatment. *Legionella* recolonized showers treated with UV after one month of operation, but when filters were added to remove particles that foul the UV lamps, the showers remained *Legionella*-free for a period of three months (Liu et al., 1995).

2.3.5.3 Potential Water Quality Issues

Water quality data is needed to adequately characterize the water to be treated by the UV reactor and identify any pre-treatment that may be required. Manufacturers may have their own data requests, though the following list will cover most water quality information needed (Alaska DEC, 2014; AWWA, 2012; GLUMRBSPPHEM, 2012; WSDOH, 2009; USEPA, 2006e):

- Temperature - Some reactor components may not be tolerant of water >35 degrees C (95 degrees F). For this reason, UV should be installed on the cold water supply upstream of water heaters and continuous hot water recirculation loops.

- 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 (also measured as 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.
- Hardness - Calcium and magnesium salts may precipitate on quartz sleeves leading to decreased UV output. A hardness of >120 mg/L is a threshold of concern (GLUMRBSPPHEM, 2012).

2.3.5.4 Operational Conditions

Parameter Conditions Indicating Operational Effectiveness

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 2006e).

Installation Considerations

There are several sources of design guidance for the application of UV disinfection on potable water supplies (Alaska DEC, 2014; AWWA, 2012; GLUMRBSPPHEM, 2012; WSDOH, 2009; USEPA, 2006e). 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 to avoid jetting and swirling flow through the UV reactor.
- Redundancy includes providing more than one UV reactor to allow for chemical cleaning and equipment maintenance.
- Valves to isolate UV reactors are necessary. In some cases, such as when UV reactors are flooded with cleaning chemicals, special valve arrangements, such as double-block-and-bleed valves, may be required 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. An uninterruptible power supply or power conditioning equipment may need to be considered.
- 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

While UV reactors are relatively simple to maintain, compared to more complex treatment equipment, they do 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. In addition, some reactor components can be affected by disinfectants, including chlorine, added prior to the reactor, and additional maintenance may be required. Most UV lamps installed in smaller reactors will typically be rated for 10,000–12,000 hours of operation (one year of continuous operation equals 8,736 hours). 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, 2006e).

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 U.S. water treatment facilities has been increasing over the last four decades (Thompson et al., 2013). 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*

Several researchers have reported rapid and effective inactivation of *Legionella*, mostly in laboratory studies (Edelstein et al., 1982; Muraca et al., 1987; Domingue et al., 1988; Jacangelo et al., 2002). They found little to no effect of pH (from 7.2–8.9), turbidity and temperature (from 25–43 degrees C, or 77–109.4 degrees F) on ozone inactivation of *L. pneumophila.* However, 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 eradicate *L. pneumophila* from the plumbing fixtures with positive cultures. The water supply was split into two wings: one treated with ozone, while the other was untreated. In their laboratory study using distilled water, more than 3-log 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).

- 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. *Legionella* 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. However, the conclusion regarding no effect of turbidity was drawn from a comparison between non-turbid water (tap water) and turbid water (containing 4 to 5 mg/L of suspended solids, prepared by making 1:10 dilution of a concentrated hot-water tank effluent sample). The turbidity of neither water was measured or reported in the paper. The report of the insignificant effect of temperature on inactivation in this study may have more to do with the experimental design (in which log-inactivation was not actually measured as a function of CT) than the inherent temperature dependence of the ozone- *L. pneumophila* reaction.

- 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 kill of *L. pneumophila* occurring during a 5-minute exposure to 0.10–0.3 mg/L ozone. They also reported little to no effect of pH on ozone inactivation of *L. pneumophila*, with pH ranging from 7.2 to 8.9. Experiments were conducted at 25, 35 and 45 degree C, and slightly lower ozone doses were required at 35 and 45 degree C than at 25 degree C. At a

higher temperature, an enhanced rate of disinfection could have been offset by a higher rate of ozone decomposition. Overall, the effect of temperature in this work is not clear.

- Jacangelo et al. (2002) conducted laboratory studies to evaluate multiple disinfectants, including ozone, for inactivation of waterborne emerging pathogens including *Legionella*. The ozone dose rate was 1.0 mg/L. The model-predicted CT values for a 2-log 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.

- Ruiz et al. (2007) designed and constructed a pilot plant to simulate the growth of *Legionella* in biofilms and to evaluate the use of ozone to reduce both *Legionella* and biofilms. They discussed technical issues with the application of ozone for control of *Legionella* in water systems, including injection methods, automation systems, liquid and gas phase online measurements, and interaction of ozone with the structure of the facility. However, no test results were reported in this paper.

2.3.6.3 Potential Water Quality Issues

Ozone itself does not form halogenated DBPs such as THMs and HAAs. However, 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 building water system. As such, bromate formation may not be as relevant as in the water treatment plant. Other ozonation byproducts include aldehydes and organic acids that are more readily biodegradable and that 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 building water system are still unclear.

2.3.6.4 Operational Conditions

Ozone disinfection is not typically impacted by pH in the range of 6 to 9. 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 CT 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.

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. Ozone is a toxic gas (e.g., being a principal component of smog). Ozone is corrosive and can corrode steel pipes and fittings, concrete, rubber gaskets and other material it comes into contact with (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).

3 Other Strategies Used to Control for *Legionella*

3.1 Emergency Remediation

Emergency remediation of a building water system is triggered by an outbreak of legionellosis associated with a potable water system, identification of suspected cases of the disease associated with a potable water system, or identification of *Legionella*-positive water results during routine environmental testing (ASHRAE, 2015; Department of Veterans Affairs, 2014). Several agencies and organizations have published standards or guidance documents on when and how to conduct emergency remediation (HSE, 2014; Department of Veterans Affairs, 2014; ASHRAE, 2015; HSE, 2009; CDC, 2003; ASHRAE, 2000). Some of these documents apply to not only building water systems but also cooling towers and evaporative condensers; whirlpool spas; decorative fountains; and other aerosol-generating air coolers, humidifiers, and air washers. This chapter provides an overview of commonly used emergency remediation methods, including superheat-and-flush disinfection, shock hyperchlorination, POU filtration, and any combination of these methods.

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. Because *Legionella* can easily be killed at temperatures >60 degrees C (140 degrees F), 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 (Department of Veterans Affairs, 2014; Sehulster and Chinn, 2003; ASHRAE, 2000). The optimal flush time reported varies from 10 to 30 minutes depending on the characteristics of the building water system. A 30-minute flush, first adopted by Best et al. (1983), is recommended as a good practice (Department of Veterans Affairs, 2014).

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.

- 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 above 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 above 55 degrees C (131 degrees F).

However, an inadequate temperature for the superheat (below 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). The shock treatment may not provide long-term control of *Legionella* if the building water system does not maintain a proper temperature or a residual chlorine level.

- 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 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, eliminated *Legionella* from 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.

- 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 *Legionella*. But recolonization occurred within 29 days of the last treatment. The heat-flush treatment failed to provide long-term control of *Legionella***.**

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.

- 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.

- 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.

- 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.

3.1.1.3 Potential Water Quality Issues

Regrowth of *Legionella* following superheat-and-flush has been identified as an issue (Stout and Yu, 2003). Recolonization could be caused by the survival properties of *Legionella* spp. (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, stagnation and low flow). Researchers have revealed that *Legionella* 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).

The superheat-and-flush method generally does not require special equipment; however, it is labor-intensive and time-consuming 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 applicable to hot water systems with sufficient heat capacity. It may be ineffective when parts of the boiler/water heater or the water system fail to reach the required temperature (Lin et al., 2000a) or in systems that do not have hot water lines to every distal site.
- 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 (Rosenblatt and McCoy, 2014). Caution must be taken during emergency disinfection to avoid potential scalding.
- The high temperature employed in this method can damage pipes and may cause failure of elastomeric seals, resulting in pump failure and leakage across valves (Rosenblatt and McCoy, 2014). Pipe material should be assessed before considering this approach.

3.1.1.4 Operational Conditions

Recommendations for conducting an effective superheat-and-flush, based on the published standards and guidelines (HSE, 2014; Department of Veterans Affairs, 2014; ASHRAE, 2015; 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 done to determine efficacy of the treatment. 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 building water 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; Department of Veterans Affairs, 2014). After a sufficient contact time, the water is flushed and the residual chlorine is returned to its normal level. 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 building water 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 building water 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 below and other studies in Section 2.3.1:

- 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 *Legionella* spp. were isolated from the more than 500 water samples collected during the 10-year period.

- García et al. (2008) conducted long-term surveillance and studied the persistence of *Legionella* 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 ppm and contact time of five hours, or a dosage rate of 20 ppm 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 *Legionella* was absent for a period of a few months. New cases of Legionnaires' disease also occurred after

hyperchlorination. The results of *Legionella* sampling 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 *Legionella*, 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 building water system, *Legionella* 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.

- A study of 62 hotels in Spain evaluated the use of continuous chlorination at 1–2 mg/L of free residual chlorine in the cold water, combined with intermittent thermal treatment in the hot water. Samples positive for *Legionella* dropped from approximately 30 percent after the first year of application, to 20 percent after three years, and to 6 percent after five years (Crespi and Ferra, 1998).

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, the same concentration used in shock hyperchlorination (Storey et al., 2004a; Kilvington and Price, 1990).

3.1.2.3 Potential Water Quality Issues

Regrowth of *Legionella* 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 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 below:

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 harbor *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 stagnation and low flow) 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 other form of long-term treatment, if cases continue to be identified or if a *Legionella* strain isolated from patients persists in the building water 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 building water 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.

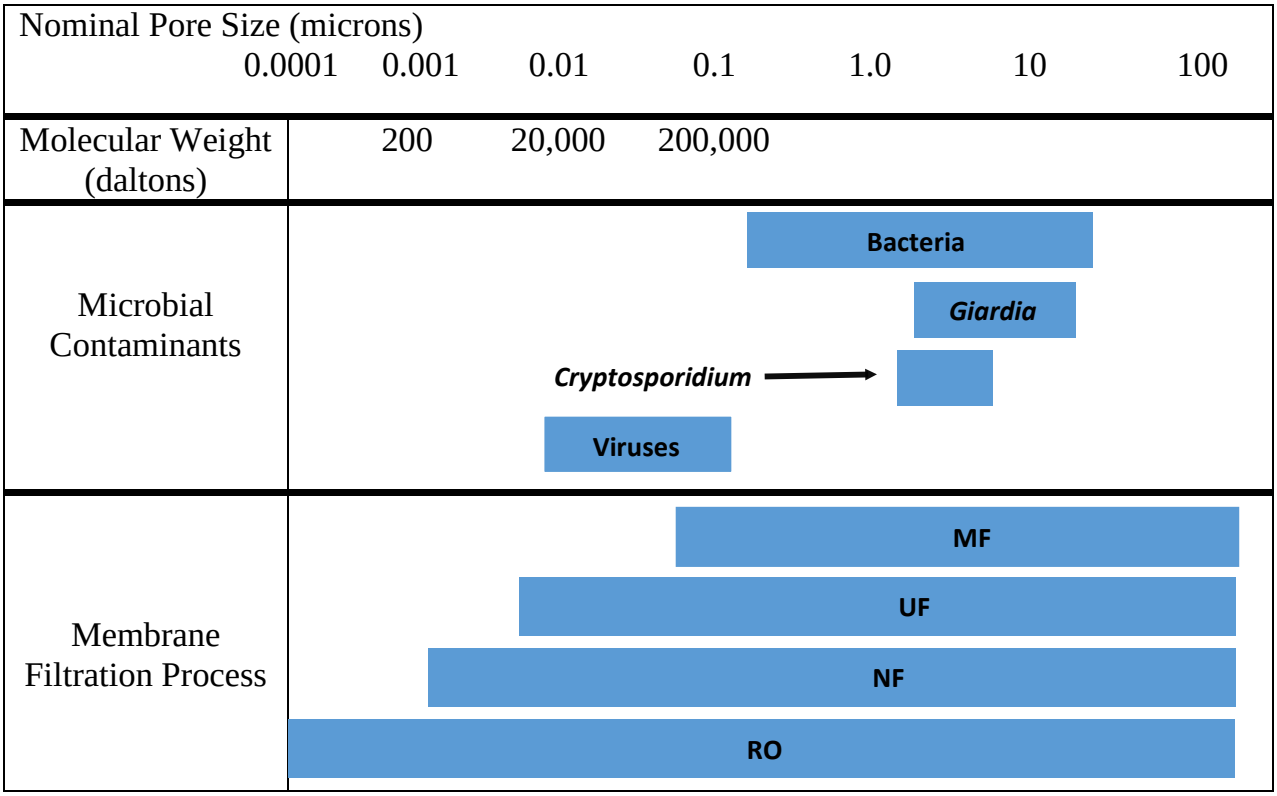
3.2 Point-of-Use Filtration

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, 2005b; 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 which 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 (Bartram et al., 2007).

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



Source: USEPA, 2005b.

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 homeowners; building 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, bone marrow and solid organ transplant, 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. (2014) evaluated a new faucet filter at five sinks in a cancer center and found that *Legionella* was 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 *Legionella* 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. *Legionella* 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 eliminated *Legionella* and mycobacteria through seven days of use and yielded a >99 percent reduction in heterotrophic bacteria.

- 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, 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 and foster growth of pathogens. Failure of filters could lead to the release of high levels of pathogens. Membranes may foul, clog with scale (from salts in feed water), 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 the EPA's *Membrane Filtration Guidance Manual* (USEPA, 2005b). 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 Building Water Systems

4.1 Public Health Concerns

Q1. What are the threats from *Legionella* in a building water system?

Legionella is a naturally occurring bacterial pathogen that can be present in municipal and other water supplies. Building water systems may provide conditions (e.g., low flow/long retention times, optimal temperature, and low disinfectant residual levels) that favor its growth to levels that may result in increased risk to public health (i.e., developing legionellosis). For more details 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 likely that most *Legionellae* can cause human disease under the appropriate conditions (e.g., in individuals in higher risk groups) (Borella et al., 2005; 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.

Building water system 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 building water operator and/or manager may want to evaluate the building water system processes that could contribute to *Legionella* growth (e.g., long hot water holding times). This assessment should allow the building water system manager to determine the necessary stringency of the control 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 codified at 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. Why do I need to comply with drinking water standards if I'm only treating the hot water (not for drinking purposes)?

EPA considers water for human consumption to include water for drinking and food preparation as well as water for brushing teeth, showering and hand washing (See 63 FR 41940; August 5, 1998).

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

The pesticide registration requirements under FIFRA are independent of the SDWA requirements, and each mandate targets complementary, yet different, environmental and public health protection objectives. Registration of a pesticide product 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 federal control of pesticide distribution, sale and use. All pesticides distributed or sold in the United States must be registered (licensed) by EPA. Registration assures that pesticides are properly labeled and that, if used in accordance with their approved labeling, they will not cause unreasonable adverse effects on the environment or human health.

Registration is required for pesticide products that are sold or distributed in the United States for antimicrobial applications. However, this requirement does not necessarily preclude the use of other disinfectants recognized under the Surface Water Treatment Rules such as chlorine, chlorine dioxide and chloramines.

The SDWA is the main federal law that ensures the quality of Americans' drinking water. Under SDWA, EPA sets standards for drinking water quality and oversees the states, localities and water suppliers who implement those standards.

While there are no requirements under SDWA that prohibit the installation of a given technology, the primacy agency is 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 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. 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. A device is subject to the FIFRA prohibition against misbranding and must be produced in an EPA-registered establishment. To be considered a device, the item must not be sold or distributed with a substance or mixture of substances to perform its intended pesticidal purpose. For example, drinking water treatment technologies that incorporate a substance (e.g., chlorine, chloramine, silver or copper in the form of an electrode) for pesticidal purposes are not considered to be pesticide devices and must be registered. Additional information on pesticide devices and the associated FIFRA requirements is available on EPA's website and includes fact sheets and a registration manual. For additional information regarding obtaining installation or operating permits see response to Question 20.

4.3 Control Measures

Q9. What measures can a building operator take to control the colonization and amplification of *Legionella* in a building water system?

Buildings can vary in their characteristics (e.g., dimensions, location with respect to the servicing PWS) as well as their purposes. The appropriate treatment depends on those characteristics and purposes. A multi-barrier approach can be used to ensure a comprehensive preventative approach is taken to address potential health risks related to the building water system. See Section 2.2 of this document for information on multi-barrier approaches.

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 assumes that if sufficient treatment is provided to control for *Giardia* and viruses (i.e., 3-log inactivation of *Giardia* and 4-log inactivation of viruses), then *Legionella* should be addressed as well. In addition, the Revised Total Coliform Rule and the Ground Water Rule have treatment technique requirements that address bacteria, which provide some control of *Legionella*. All of these rules apply to PWSs. They would not apply to building water 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 added, such as that added to reduce *Legionella,* to supplement or boost the treatment provided by the distributor of the water being received. To address water quality and pathogen control needs, building operators and owners, after a careful review of building and water system conditions, may wish to implement a supplemental application of a disinfectant specific to and within the building water system. Supplemental treatment in this case does not refer to emergency disinfection by the building owner or operator (i.e., water disinfected as a result of the emergency that is not intended for human consumption).

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

You will need to determine whether the application of that treatment triggers additional SDWA requirements, for example, requiring the building water system to be fully regulated as a PWS. You may wish to consult with your water supplier (i.e., PWS) to better understand any potential water quality issues before making treatment-related decisions. If a decision to add treatment to the building water system seems likely, EPA advises building owners to consult with their primacy agency to determine if any SDWA requirements apply; in addition, there may be state or local requirements that apply to the treatment or the water system. See Section 1.4 for additional information.

Q14. What should I do before I consider supplemental water treatment?

Building owners and operators considering the addition of a supplemental water treatment system are encouraged to contact their primacy agency and other state and local authorities and familiarize themselves with applicable federal, state and local regulations (e.g., building codes, local health codes). Building owners and operators should also become very familiar with the characteristics and needs of their system to help determine the most appropriate supplemental water treatment. Please see Section 2.3 of this document for more information on treatment 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 ensure that a high level of water quality is maintained, improving public health protection and reducing liabilities. Providing supplemental disinfection can help maintain the high level of water quality throughout the building water system.

Q16. Are there any disadvantages to supplemental disinfection?

Operating supplemental water treatment requires the commitment of financial, physical and staff resources. An additional disadvantage is that installation of supplemental treatment could lead to

a false sense of security. Installation of supplemental disinfection does not negate the need for building owners/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 new treatment technologies to control *Legionella* in drinking water?

Rather than approve new treatment technologies, EPA recognizes them 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. The 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) 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. Note that new technologies may need to comply with registration or other requirements for pesticide products and devices under FIFRA (See response to Question 8).

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 building/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 30 (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 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 regardless 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 DBPs do I need to monitor?

The Stage 1 DBPR and Stage 2 DBPR established MCLs for DBPs and MRDLs for disinfectant residuals. It also specified the monitoring requirements that PWSs must perform for residual disinfectants and DBPs (type, frequency and location), depending on the type of systems, population served and type of disinfectants being used. For example, a regulated PWS using chlorine or chloramine must monitor for TTHM, HAA5 and residual chlorine. A regulated PWS using chlorine dioxide must monitor for TTHM, HAA5, chlorite and chlorine dioxide. See the Stage 2 DBPR Quick Reference Guide for more information.

Q23. How do I monitor for chlorine dioxide?

For regulated PWSs, chlorine dioxide is a contaminant with acute health effects and must be monitored daily at the entry point to the distribution system and at each treatment unit location to ensure it is not exceeding the MRDL of 0.8 mg/L. Chlorine dioxide has a short sample hold time and must be measured immediately after collection; therefore, on-site analysis at the water system is required.

The approved analytical methods for measuring residual disinfectant concentration for chlorine dioxide include Standard Method 4500-ClO_2 D and E (40 CFR 141.131(c)). These methods indicate that systems may also measure residual disinfectant concentrations for chlorine dioxide by using DPD colorimetric test kits, and the person conducting the measurements must be approved by EPA or the state.

Facilities considering installation of this technology should coordinate with the primacy agency to determine requirements for approval. Some primacy agencies are requiring the water systems' staff members who are conducting on-site analysis of chlorine dioxide and chlorite to prove analytical competency by performing an initial demonstration of capability as well as an ongoing demonstration of capability.

Q24. Can I send daily chlorite and chlorine dioxide samples to a lab?

If you are subject to Stage 2 requirements, you are required to analyze daily chlorite samples on-site and send monthly chlorite samples to a certified laboratory (see table footnote 8 in 40 CFR 141.131(b)). You cannot send daily chlorine dioxide samples to a laboratory for analysis because

chlorine dioxide has a short sample hold time and must be measured on-site immediately after collection.

Q25. Does EPA require *Legionella* monitoring if treatment for its control is installed? If so, what are the targets for meeting control?

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

Q26. 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, 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 PWSs might have 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

Q27. What is operator certification?

Operator certification is a program that establishes minimum professional standards for the operation and maintenance of PWSs to help protect human health and the environment. In 1999, EPA issued operator certification program guidelines specifying minimum standards for certification and recertification of the operators of community and non-transient non-community PWSs. These guidelines are currently being implemented through state operator certification programs. While the specific requirements vary from state to state, the goal of all operator certification programs is to ensure that skilled professionals are overseeing the treatment and distribution of safe drinking water. Operator certification is an important step in promoting compliance with SDWA. More information on operator certification is available on EPA's website.

Q28. Do I need to have a certified operator for this treatment system?

If your facility is a regulated PWS, (see questions in Section 4.2 to determine if you are regulated), you may be required to have a certified operator for your treatment system. There are two general types of operator certification — one for treatment systems and one for distribution systems. Within each type, there are different levels of certification. Consult with your primacy agency to determine the type and level of certified operator required for your specific system.

4.8 Unintended Consequences

Q29. 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 specific treatment sections in this document.

4.9 Additional Sources of Information

Q30. 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

5 References

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A Appendix

A.1 Elements of Hazard Analysis and Critical Control Points (HACCP)

HACCP is based on an engineering concept of failure, mode and effects analysis. It has five initial steps followed by seven main principles (Mortimore and Wallace, 2001).

The five initial steps are below (FAO, 1998):

- **Step 1:** Assemble HACCP team
- **Step 2:** Describe the product
- **Step 3:** Identify intended use
- **Step 4:** Construct a process flow diagram
- **Step 5:** Verification of the process flow diagram

The seven principles include the following:

- **Principle 1:** Conduct a hazard analysis
- **Principle 2:** Determine the critical control points
- **Principle 3:** Establish critical limit(s)
- **Principle 4:** Establish a system to monitor control of critical control points
- **Principle 5:** Establish corrective actions
- **Principle 6:** Validate/verify HACCP plan
- **Principle 7:** Establish documentation and recordkeeping procedures

The first step, assembling the HACCP team, is best completed by bringing together a multi-disciplinary team. The team may consist of a lead coordinator along with team members representing different areas of expertise or responsibilities for managing the building water system. This can include but is not limited to building managers, building water system operators, engineers, maintenance staff, laboratory managers, plumbing experts, public health risk assessors, financial experts and environmental health specialists. In some cases, the HACCP team may include external experts (WHO, 2011; Mortimore and Wallace, 2001). The inclusion of staff with a broad range of expertise helps to ensure that all priority risks will be identified and decisions on control measures will be practical to implement (Martel et al., 2006). The roles (e.g., task manager, trainer, lead reviewer), responsibilities (e.g., collecting samples) and expertise (e.g., backflow prevention, water treatment) of each team member are usually summarized in the HACCP plan.

The second step involves describing the product, in this case the building water. The description usually includes water characteristics such as pH, storage conditions, temperatures, current treatment, and source water information (e.g., the type of treatment that was applied to the water prior to it reaching the building service connection, how/where the water was stored and distributed throughout the PWS, and standards the water must meet before it reaches the service connection) (USEPA, 2006a).

The third step is to identify the intended use(s) of the water. Examples can include drinking, bathing, swimming, cleaning, laundry, flushing toilets, building heating, cooling and fire

protection. These intended uses can help indicate the different routes of exposures such as consumption, inhalation and dermal absorption (WHO, 2005). The intended uses may vary depending on the type of facility containing the building water system. For example, a hospital might have additional water uses that a hotel or condominium would not have, and vice versa. The population using the water will also vary among different types of facilities (e.g., a nursing home will most likely have a larger elderly and immunocompromised population than a hotel).

The fourth step is to construct a process flow diagram. This diagram describes in detail the building water system from the point where the water is first received (the building service connection) to where the water meets its intended uses, such as at the tap for consumption, showering, flushing toilets, or a hot tub. This diagram will include all aspects of the building water system, such as hot water networks, cold water networks, equipment installed at point-of-use (e.g., filters), backflow prevention assemblies, and cross connections (direct and indirect). Descriptions of the water at different points in the system are also usually included, such as temperatures in the hot and cold water networks, pressures at backflow prevention devices, and water age throughout the system. Water uses and patterns are also important to include within the process flow diagram, including intended and unintended uses (WHO, 2011).

The fifth step is to verify the process flow diagram. This refers to an on-site visual inspection of the entire building water system during initial development of the HACCP plan and periodic review after construction or maintenance work. The periodic review occurs during various times to ensure accuracy during all operational processes. Not only does this step ensure all of the different operational aspects of the building water system are accounted for, it also confirms the different uses and use patterns in the process flow diagram (FAO, 1998). During the on-site inspection, the HACCP team confirms that the building water system meets applicable codes (Rosenblatt and McCoy, 2014).

After the five initial steps have been completed, the seven principles of HACCP are initiated. The first principle of HACCP involves conducting a hazard analysis to identify and prioritize possible hazards in a particular building water system and to identify appropriate control measures. Hazards within a building water system can be biological, chemical, radiological or physical. These can occur at many points throughout the entire building water system (WHO, 2011; FAO, 1998). An example of a physical hazard in a building water system is scalding due to hot water or steam (Rosenblatt and McCoy, 2014). An example of chemical exposure is lead leaching from pipework, and an example of microbial exposure is *Legionella* growing in biofilms. Along with identifying hazards, it is important to specify how likely the contaminant or hazard is to occur, the different control measures put in place for the identified hazard, and the severity of consequences of the hazard occurring (Martel et al., 2006; USEPA, 2006a).

The second principle of HACCP is identification of critical control points (FAO, 1998). Critical control points are specific points in the building water system that are essential to preventing and eliminating hazards and where controls can be applied (new or controls currently in place) (FAO, 1998). Decision trees can be useful tools in determining which control points are critical (Mortimore and Wallace, 2001). Examples of critical control points in a building water system can include hot water heaters, the location where disinfection is applied, locations where backflow prevention assemblies are installed or should be installed, the location of POU controls, and the points at which routine flushing is conducted.

The third HACCP principle is establishment of critical limits for the control measures employed at each critical control point. These critical limits are measurable criteria that separate safe from potentially unsafe conditions (WHO, 2011; Mortimore and Wallace, 2001). Examples of critical limits in a building water system can include temperature ranges for a hot water heater, temperature ranges for hot and cold water lines, disinfectant levels at the point of application or at distal taps, and the frequency for changing POU filters.

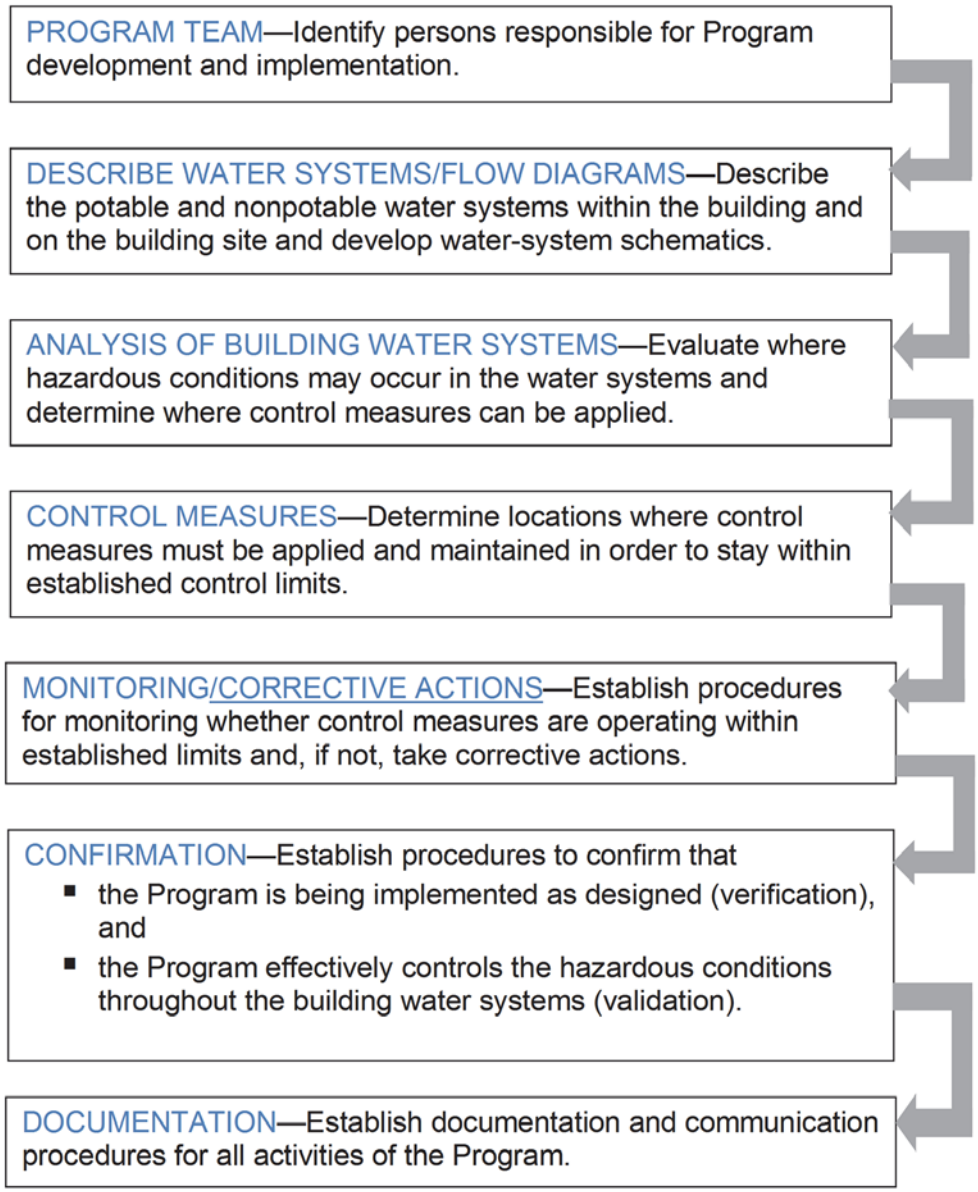
The fourth HACCP principle is identification of monitoring procedures for each critical limit set for each control point (Mortimore, 2001; WHO, 2011). The monitoring procedures describe what parameter is being monitored, the monitoring frequency and location, monitoring methods, and reporting and recordkeeping procedures. According to FAO (1998) the procedures should also identify staff responsible for each aspect of the monitoring procedures, such as which staff are responsible for sample collection and analysis.

The fifth HACCP principle is the establishment of corrective actions. When a critical limit is exceeded, the corrective action procedure will be carried out to restore values to the expected range. The procedure will also include processes for determining the cause of the exceedance to ensure it does not recur (FAO, 1998). For example, if the disinfectant residual at distal taps is too low, the corrective action may include increasing the chemical dosage rate or boosting it at another location in the system. Other corrective action procedures for managing critical limits within building water systems could include maintenance on equipment, inspecting chemical feed pumps, inspecting boiler controls, preventing the use of contaminated water (e.g., providing bottled water, shutting off the tap, using an alternative water source), superheating the system, and flushing the piping system (WHO, 2011). Similar to monitoring procedures described under the fourth principle, corrective action procedures identify the staff responsible for each task.

The sixth HACCP principle is establishment of verification and validation procedures. The validation step ensures the system is safe from hazards and that the HACCP plan is effectively controlling for hazards. Validation may include monitoring physical, chemical or microbiological parameters, as well as review of clinical surveillance data. Validation can also help identify unnecessary and ineffective control measures (Rosenblatt and McCoy, 2014; Mortimore, 2001; FAO, 1998). The verification step ensures the HACCP plan is working correctly and provides evidence that the HACCP plan is being implemented as intended. Verification activities may involve a supervisor checking that staff members have performed monitoring, maintenance and recordkeeping tasks outlined in the HACCP plan.

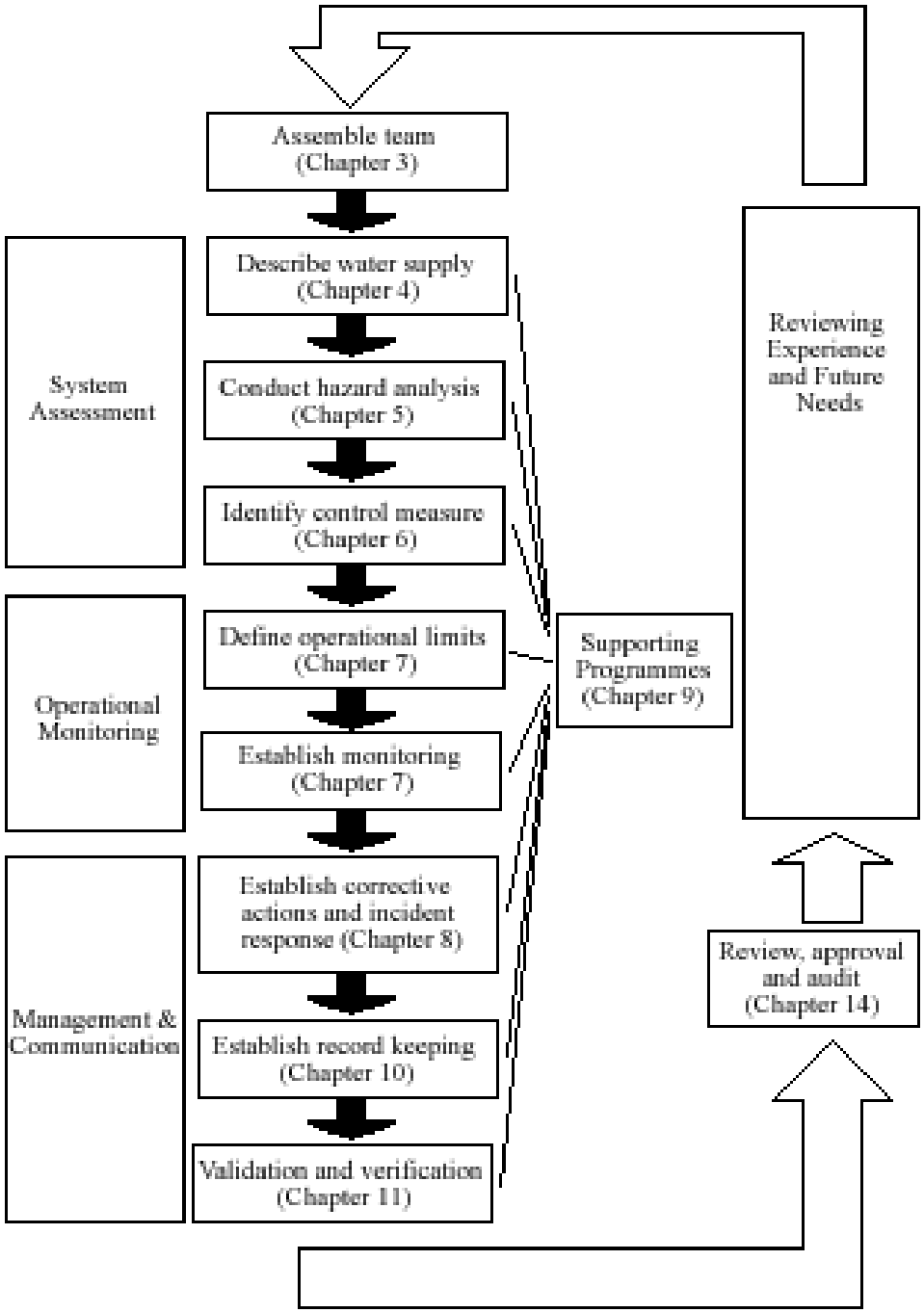
The seventh HACCP principle is the establishment of documentation and recordkeeping. It is imperative to the HACCP process that complete and accurate records are maintained (FAO, 1998). Recordkeeping allows the HACCP team to track the system's performance of the HACCP plan as well as the performance of control measures (USEPA, 2006a). In the event that a water system experiences a waterborne disease outbreak or another water quality event that could affect public health, historical water quality data and system records can be helpful to prove due diligence (i.e., that appropriate steps were taken to control known hazards).

A.2 Elements of a Water Management Program



Source: ASHRAE, 2015.

A.3 Elements of Water Safety Plan



Source: WHO, 2005.