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

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

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

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

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

2.3 Technologies

2.3.1 Chlorine

2.3.1.1 Background

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

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

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

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

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

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

2.3.1.2 Characterization of Effectiveness against *Legionella*

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

2.3.1.3 Potential Water Quality Issues

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

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

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

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

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

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

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

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

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

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

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

2.3.1.4 Operational Conditions

Parameter Conditions Indicating Operational Effectiveness

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

Installation Considerations

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

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

Monitoring Frequency and Location

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

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

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

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

Maintenance Needs

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

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

2.3.2 Monochloramine

2.3.2.1 Background

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

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