

2.7 Chlorine

Although chlorine is not a focus of this guidance manual, the following section provides a brief overview of chlorine use in the water treatment industry to compare with the alternative disinfectants discussed in this manual. Since there is a wealth of excellent literature on chlorine's uses and performance capabilities, summarizing this large body of knowledge here is neither practical nor necessary (see, for example: White, 1992; Chlorine Institute, 1996; and Connell, 1996).

One of the recent developments in chlorine disinfection is the use of multiple and interactive disinfectants. In these applications, chlorine is combined with a second disinfectant to achieve improved disinfection efficiency and/or effective DBP control. A detailed discussion on multiple disinfectants, including chlorine combinations, is provided in Chapter 9.

As described earlier, the 1995 Community Water System Survey (USEPA, 1997a), indicated that the majority of all surface water and ground water systems in the United States use chlorine for disinfection.

Chlorine has many attractive features that contribute to its wide use in the industry. Four of the key attributes of chlorine are that it:

- Effectively inactivates a wide range of pathogens commonly found in water;
- Leaves a residual in the water that is easily measured and controlled;
- Is economical; and
- Has an extensive track record of successful use in improving water treatment operations (despite the dangers associated with chlorine application and handling, specifically chlorine gas, it still maintains an excellent safety record).

There are, however, some concerns regarding chlorine usage that may impact its uses such as:

- Chlorine reacts with many naturally occurring organic and inorganic compounds in water to produce undesirable DBPs;
- Hazards associated with using chlorine, specifically chlorine gas, require special treatment and response programs; and
- High chlorine doses can cause taste and odor problems.

Chlorination is used in water treatment facilities primarily for disinfection. Because of chlorine's oxidizing powers, it has been found to serve other useful purposes in water treatment, such as (White, 1992):

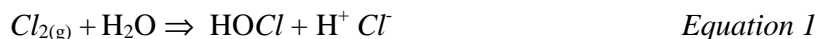
- Taste and odor control;
- Prevention of algal growths;
- Maintenance of clear filter media;
- Removal of iron and manganese;
- Destruction of hydrogen sulfide;
- Bleaching of certain organic colors;
- Maintenance of distribution system water quality by controlling slime growth;
- Restoration and preservation of pipeline capacity;
- Restoration of well capacity, water main sterilization; and
- Improved coagulation by activated silica.

2.7.1 Chlorine Chemistry

Chlorine for disinfection typically is used in one of three forms: chlorine gas, sodium hypochlorite, or calcium hypochlorite. A brief description of the chemistry of these three chemicals is provided below.

2.7.1.1 Chlorine Gas

Chlorine gas hydrolyzes rapidly in water to form hypochlorous acid (HOCl). The following equation presents the hydrolysis reaction:



Note that the addition of chlorine gas to water reduces the pH of the water due to the production of hydrogen ion.

Hypochlorous acid is a weak acid (pK_a of about 7.5), meaning it dissociates slightly into hydrogen and hypochlorite ions as noted in Equation 2:



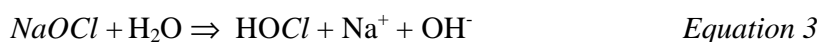
Between a pH of 6.5 and 8.5 this dissociation is incomplete and both HOCl and OCl⁻ species are present to some extent (White, 1992). Below a pH of 6.5, no dissociation of HOCl occurs, while above a pH of 8.5, complete dissociation to OCl⁻ occurs. As the germicidal effects of HOCl is much higher than that of OCl⁻, chlorination at a lower pH is preferred.

2.7.1.2 Hypochlorite

In addition to chlorine gas, chlorine is also available in hypochlorite form as both aqueous solutions and dry solids. The most common aqueous hypochlorite solution is sodium hypochlorite. The most common form of dry solid hypochlorite is calcium hypochlorite (White, 1992).

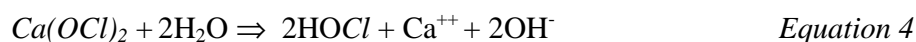
Sodium Hypochlorite. Sodium hypochlorite is produced when chlorine gas is dissolved in a sodium hydroxide solution. Sodium hypochlorite solution typically contains 12.5 percent available chlorine (White, 1992). One gallon of 12.5 percent sodium hypochlorite solution typically contains the equivalent of one pound of chlorine.

The reaction between sodium hypochlorite and water is shown in the following reaction:



Equation 3 shows that the application of sodium hypochlorite to water produces hypochlorous acid, similar to chlorine gas hydrolysis (Equation 1). However, unlike chlorine hydrolysis, the addition of sodium hypochlorite to water yields a hydroxyl ion that will increase the pH of the water. In addition, excess sodium hydroxide is used to manufacture sodium hypochlorite, which will further increase the pH of the water.

Calcium Hypochlorite. Calcium hypochlorite is formed from the precipitate that results from dissolving chlorine gas in a solution of calcium oxide (lime) and sodium hydroxide. Granular calcium hypochlorite commercially available typically contains 65 percent available chlorine. This means that 1.5 pounds of calcium hypochlorite contains the equivalent of one pound of chlorine. The reaction between calcium hypochlorite and water is shown in the following reaction:



Equation 4 shows that the application of calcium hypochlorite to water also produces hypochlorous acid, similar to chlorine gas hydrolysis (Equation 1). Similar to sodium hypochlorite solution, the addition of calcium hypochlorite to water yields hydroxyl ions that will increase the pH of the water.

2.7.2 Chlorine Generation

Onsite generation of chlorine has recently become practical. These generation systems, using only salt and electric power, can be designed to meet disinfection and residual standards and to operate unattended at remote sites. Considerations for chlorine generation include cost, concentration of the brine produced, availability of raw materials, and the reliability of the process (AWWA and ASCE, 1997).

2.7.2.1 Chlorine

Chlorine gas can be generated by a number of processes including the electrolysis of alkaline brine or hydrochloric acid, the reaction between sodium chloride and nitric acid, or the oxidation of

hydrochloric acid. About 70 percent of the chlorine produced in the United States is manufactured from the electrolysis of salt brine and caustic solutions in a diaphragm cell (White, 1992). Since chlorine is a stable compound, it is typically produced off-site by a chemical manufacturer. Once produced, chlorine is packaged as a liquefied gas under pressure for delivery to the site in railcars, tanker trucks, or cylinders.

2.7.2.2 Sodium Hypochlorite

Dilute sodium hypochlorite solutions (less than 1 percent) can be generated electrochemically on-site from salt brine solution. Typically, sodium hypochlorite solutions are referred to as liquid bleach or Javelle water. Generally, the commercial or industrial grade solutions produced have hypochlorite strengths of 10 to 16 percent. The stability of sodium hypochlorite solution depends on the hypochlorite concentration, the storage temperature, the length of storage (time), the impurities of the solution, and exposure to light. Decomposition of hypochlorite over time can affect the feed rate and dosage, as well as produce undesirable byproducts such as chlorite ions or chlorate (Gordon et al., 1995). Because of the storage problems, many systems are investigating onsite generation of hypochlorite in lieu of its purchase from a manufacturer or vendor (USEPA, 1998b).

2.7.2.3 Calcium Hypochlorite

To produce calcium hypochlorite, hypochlorous acid is made by adding chlorine monoxide to water and then neutralizing it with a lime slurry to create a solution of calcium hypochlorite. The water is removed from the solution, leaving granulated calcium hypochlorite. Generally, the final product contains up to 70 percent available chlorine and 4 to 6 percent lime. Storage of calcium hypochlorite is a major safety consideration. It should never be stored where it is subject to heat or allowed to contact any organic material of an easily oxidized nature (USEPA, 1998b).

2.7.3 Primary Uses and Points of Application of Chlorine

2.7.3.1 Uses

The main usage of chlorine in drinking water treatment is for disinfection. However, chlorine has also found application for a variety of other water treatment objectives such as, the control of nuisance organisms, oxidation of taste and odor compounds, oxidation of iron and manganese, color removal, and as a general treatment aid to filtration and sedimentation processes (White, 1992; Connell, 1996; Culp/Wesner/Culp, 1986). Table 2-18 presents a summary of chlorine uses and doses.

Table 2-18. Chlorine Uses and Doses

Application	Typical Dose	Optimal pH	Reaction Time	Effectiveness	Other Considerations
Iron	0.62 mg/mg Fe	7.0	less than 1 hour	Good	
Manganese	0.77 mg/mg Mn	7–8 9.5	1–3 hour minutes	Slow kinetics	Reaction time increases at lower pH
Biological growth	1–2 mg/L	6–8	NA	Good	DBP formation
Taste/odor	Varies	6–8	Varies	Varies	Effectiveness depends on compound
Color removal	Varies	4.0–6.8	Minutes	Good	DBP formation
Zebra mussels	2–5 mg/L 0.2–0.5 mg/L ^(a)		Shock level Maintenance level	Good	DBP formation
Asiatic clams	0.3–0.5 mg/L ^(a)		Continuous	Good	DBP formation

Notes:

^(a) Residual, not dose

Sources: Adapted in part from White, 1992; Connell, 1996; Culp/Wesner/Culp, 1986.

2.7.3.2 Points of Application

At conventional surface water treatment plants, chlorine is typically added for prechlorination at either the raw water intake or flash mixer, for intermediate chlorination ahead of the filters, for postchlorination at the filter clearwell, or for rechlorination of the distribution system (Connell, 1996). Table 2-19 summarizes the typical uses for each point of application.

Table 2-19. Typical Chlorine Points of Application and Uses

Point of Application	Typical Uses
Raw Water Intake	Zebra mussel and Asiatic clam control, control biological growth
Flash Mixer (prior to sedimentation)	Disinfection, iron and manganese oxidation, taste and odor control, oxidation of hydrogen sulfide
Filter Influent	Disinfection, control biological growth in filter, iron and manganese oxidation, taste and odor control, algae control, color removal
Filter Clearwell	Disinfection
Distribution System	Maintain disinfectant residual

Sources: Connell, 1996; White, 1992; AWWA, 1990.

2.7.3.3 Typical Doses

Table 2-20 shows the typical dosages for the various forms of chlorine. The wide range of chlorine gas dosages most likely represents its use as both an oxidant and a disinfectant. While sodium hypochlorite and calcium hypochlorite can also serve as both an oxidant and a disinfectant, their higher cost may limit their use.

Table 2-20. Typical Chlorine Dosages at Water Treatment Plants

Chlorine Compound	Range of Doses
Calcium hypochlorite	0.5–5 mg/L
Sodium hypochlorite	0.2–2 mg/L
Chlorine gas	1–16 mg/L

Source: SAIC, 1998, as adapted from EPA's review of public water systems' Initial Sampling Plans which were required by EPA's Information Collection Rule (ICR)

2.7.4 Pathogen Inactivation and Disinfection Efficacy

2.7.4.1 Inactivation Mechanisms

Research has shown that chlorine is capable of producing lethal events at or near the cell membrane as well as affecting DNA. In bacteria, chlorine was found to adversely affect cell respiration, transport, and possibly DNA activity (Haas and Engelbrecht, 1980). Chlorination was found to cause an immediate decrease in oxygen utilization in both *Escherichia coli* and *Candida parapsilosis* studies. The results also found that chlorine damages the cell wall membrane, promotes leakage through the cell membrane, and produces lower levels of DNA synthesis for *Escherichia coli*, *Candida parapsilosis*, and *Mycobacterium fortuitum* bacteria. This study also showed that chlorine inactivation is rapid and does not require bacteria reproduction (Haas and Engelbrecht, 1980). These observations rule out mutation or lesions as the principal inactivation mechanisms since these mechanisms require at least one generation of replication for inactivation to occur.

2.7.4.2 Environmental Effects

Several environmental factors influence the inactivation efficiency of chlorine, including water temperature, pH, contact time, mixing, turbidity, interfering substances, and the concentration of available chlorine. In general, the highest levels of pathogen inactivation are achieved with high chlorine residuals, long contact times, high water temperature, and good mixing, combined with a low pH, low turbidity, and the absence of interfering substances. Of the environmental factors, pH and temperature have the most impact on pathogen inactivation by chlorine. The effect of pH and temperature on pathogen inactivation are discussed below.

pH. The germicidal efficiency of hypochlorous acid (HOCl) is much higher than that of the hypochlorite ion (OCl⁻). The distribution of chlorine species between HOCl and OCl⁻ is determined by pH, as discussed above. Because HOCl dominates at low pH, chlorination provides more effective disinfection at low pH. At high pH, OCl⁻ dominates, which causes a decrease in disinfection efficiency.

The inactivation efficiency of gaseous chlorine and hypochlorite is the same at the same pH after chlorine addition. Note, however, that addition of gaseous chlorine will decrease the pH (see Equation 1) while the addition of hypochlorite will increase the pH of the water (see Equation 3 and

Equation 4). Therefore, without pH adjustment to maintain the same treated water pH, gaseous chlorine will have greater disinfection efficiency than hypochlorite.

The impact of pH on chlorine disinfection has been demonstrated in the field. For example, virus inactivation studies have shown that 50 percent more contact time is required at pH 7.0 than at pH 6.0 to achieve comparable levels of inactivation. These studies also demonstrated that a rise in pH from 7.0 to 8.8 or 9.0 requires six times the contact time to achieve the same level of virus inactivation (Culp and Culp, 1974). Although these studies found a decrease in inactivation with increasing pH, some studies have shown the opposite effect. A 1972 study reported that viruses were more sensitive to free chlorine at high pH than at low pH (Scarpino et al., 1972).

Temperature. For typical drinking water treatment temperatures, pathogen inactivation increases with temperature. Virus studies indicate that the contact time should be increased by two to three times to achieve comparable inactivation levels when the water temperature is lowered by 10°C (Clarke et al., 1962).

2.7.4.3 Disinfection Efficacy

Since its introduction, numerous investigations have been made to determine the germicidal efficiency of chlorine. Although there are widespread differences in the susceptibility of various pathogens, the general order of increasing chlorine disinfection difficulty are bacteria, viruses, and then protozoa.

Bacteria Inactivation. Chlorine is an extremely effective disinfectant for inactivating bacteria. A study conducted during the 1940s investigated the inactivation levels as a function of time for *E. coli*, *Pseudomonas aeruginosa*, *Salmonella typhi*, and *Shigella dysenteriae* (Butterfield et al., 1943). Study results indicated that HOCl is more effective than OCl⁻ for inactivation of these bacteria. These results have been confirmed by several researchers that concluded that HOCl is 70 to 80 times more effective than OCl⁻ for inactivating bacteria. (Culp/Wesner/Culp, 1986).

Virus Inactivation. Chlorine has been shown to be a highly effective viricide. One of the most comprehensive virus studies was conducted in 1971 using treated Potomac estuary water (Liu et al., 1971). The tests were performed to determine the resistance of 20 different enteric viruses to free chlorine under constant conditions of 0.5 mg/L free chlorine and a pH and temperature of 7.8 and 2°C, respectively. In this study, the least resistant virus was found to be reovirus and required 2.7 minutes to achieve 99.99 percent inactivation (4 log removal). The most resistant virus was found to be a poliovirus, which required more than 60 minutes for 99.99 inactivation. The corresponding CT range required to achieve 99.99 percent inactivation for all 20 viruses was between 1.4 to over 30 mg·min/L.

Virus survival studies have also been conducted on a variety of both laboratory and field strains (AWWA, 1979). All of the virus inactivation tests in this study were performed at a free chlorine residual of 0.4 mg/L, a pH of 7.0, a temperature of 5°C, and contact times of either 10, 100, or 1,000 minutes. Test results showed that of the twenty cultures tested only two poliovirus strains reached

99.99 percent inactivation after 10 minutes (CT = 4 mg·min/L), six poliovirus strains reached 99.99 percent inactivation after 100 minutes (CT = 40 mg·min/L), and 11 of the 12 polioviruses plus one *Coxsackievirus* strain (12 out of a total of 20 viruses) reached 99.99 percent inactivation after 1,000 minutes (CT = 400 mg·min/L).

Protozoa Inactivation. Chlorine has been shown to have limited success inactivating protozoa. Data obtained during a 1984 study indicated that the resistance of *Giardia* cysts are two orders of magnitude higher than that of enteroviruses and more than three orders of magnitude higher than the enteric bacteria (Hoff et al., 1984). CT requirements for *Giardia* cysts inactivation when using chlorine as a disinfectant has been determined for various pH and temperature conditions (AWWA, 1991). These CT values increase at low temperatures and high pH (See also Table 2-13).

Chlorine has little impact on the viability of *Cryptosporidium* oocysts when used at the relatively low doses encountered in water treatment (e.g., 5 mg/L). Approximately 40 percent removals (0.2 log) of *Cryptosporidium* were achieved at CT values of both 30 and 3,600 mg·min/L (Finch et al., 1994). Another study determined that “no practical inactivation was observed” when oocysts were exposed to free chlorine concentrations ranging from 5 to 80 mg/L at pH 8, a temperature of 22°C, and contact times of 48 to 245 minutes (Gyürék et al., 1996). CT values ranging from 3,000 to 4,000 mg·min/L were required to achieve 1-log of *Cryptosporidium* inactivation at pH 6.0 and temperature of 22°C. During this study, one trial in which oocysts were exposed to 80 mg/L of free chlorine for 120 minutes was found to produce greater than 3-logs of inactivation.

2.7.4.4 CT Curves

Chlorine is regarded as a strong disinfectant that is effective at inactivating bacteria and viruses, and under certain circumstances, *Giardia*. Because of chlorine’s extremely high virus inactivation efficiency, CT values are almost always governed by protozoa inactivation. For example, Figure 2-1 shows the CT values required to achieve between 0.5 and 3-logs of virus and *Giardia* inactivation (AWWA, 1991). As shown, the CT values required to achieve the recommended disinfection efficiency for conventional filtration systems (i.e., 0.5-log *Giardia* cyst and 2-log virus inactivation level) are 23 and 3 mg min/L, respectively.

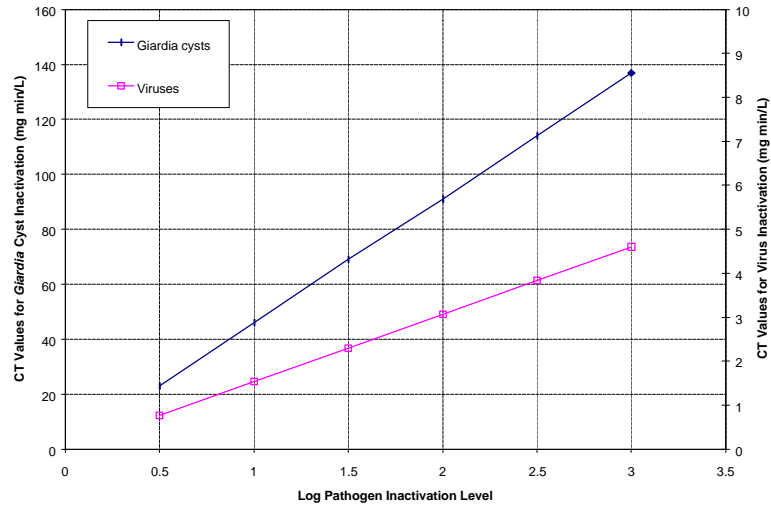


Figure 2-1. Free Chlorine *Giardia* and Virus CT Requirements

CT values for *Giardia* inactivation for various pH values and temperatures at a chlorine dose of 3.0 mg/L are shown in Figures 2-2 and 2-3. As shown, the inactivation efficacy of free chlorine decreases with increasing pH and/or decreasing temperature. CT values shown in Figures 2-2 and 2-3 are based on animal infectivity and excystation studies. CT values ranging from 0.5 to 3-log inactivation at temperatures of 0.5 and 5°C were based on a multiplicative model, and applying first order kinetics to the 99 percent upper confidence interval of the 99.99-percentile CT values. CT values for temperatures above 5°C were estimated by assuming a twofold decrease for every 10°C decrease in temperature.

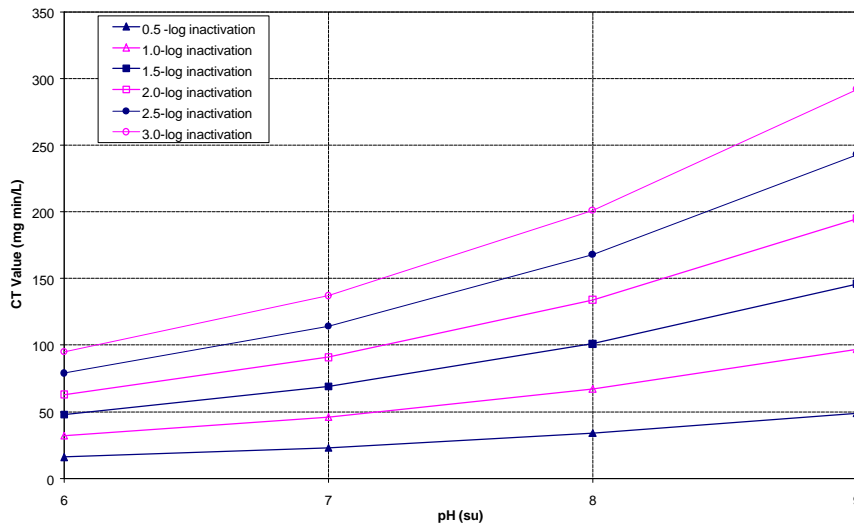


Figure 2-2. CT Values for Inactivation of *Giardia* Cysts by Free Chlorine at 10°C (at Cl₂ dose of 3.0 mg/L)

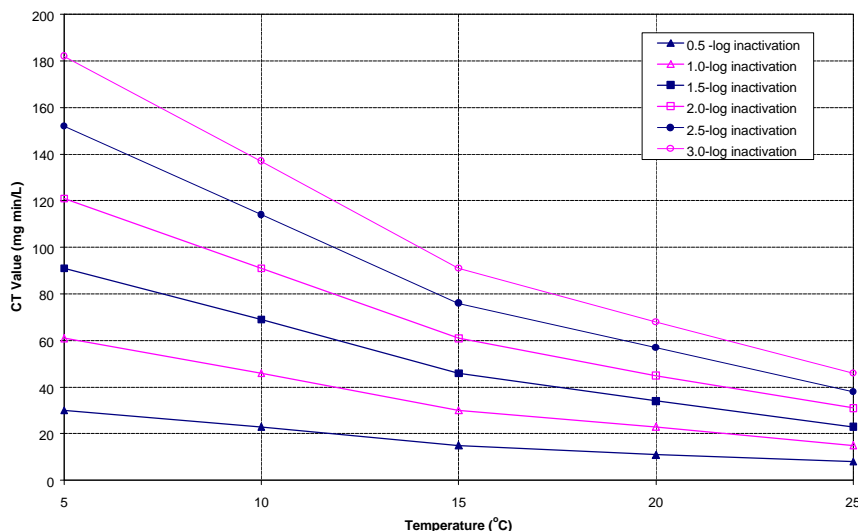


Figure 2-3. CT Values for Inactivation of *Giardia* Cysts by Free Chlorine at pH 7.0 (at Cl₂ dose of 3.0 mg/L)

2.7.5 DBP Formation and Control

2.7.5.1 DBP Formation

Halogenated organics are formed when natural organic matter (NOM) reacts with free chlorine or free bromine. Free chlorine is normally introduced into water directly as a primary or secondary disinfectant. Free bromine results from the oxidation by chlorine of the bromide ion in the source water. Factors affecting the formation of these halogenated DBPs include type and concentration of NOM, chlorine form and dose, time, bromide ion concentration, pH, organic nitrogen concentration, and temperature. Organic nitrogen significantly influenced the formation of nitrogen containing DBPs, including haloacetonitriles, halopicrines, and cyanogen halides (Reckhow et al., 1990; Hoigné and Bader, 1988).

The formation of DBPs is strongly related to TOC at the point of disinfection. DBP formation also correlates with the amount of chlorine consumed (Singer et al., 1995). Stevens et al. (1989) found that higher TTHM formation occurs at high pH (9.4) than at low pH (5.0) while HAA showed no clear trend as a function of pH. A survey of 35 water utilities conducted by MWDSC (Krasner et al., 1989) showed the median TTHM and HAA concentrations measured as 39 and 19 µg/L (i.e. more THMs than HAAs are formed). However, a subsequent study by Singer et al. (1995) found a reversal in dominance, with more HAAs than THMs produced in waters from North Carolina utilities. They postulated that the reason for this change is due to the lower pH levels and differences in TOC and bromide concentrations in the North Carolina waters. Pourmoghaddas et al. (1993) showed that brominated and mixed brominated/chlorinated THMs and HAAs are formed when using chlorine in the presence of bromide.

The occurrence of THMs and HAAs is important because regulatory limits are placed on both groups of compounds. One water utility may therefore find that its chlorination practice is limited by the production of THMs, while another will find that HAAs limit the use of chlorine. This distribution of THMs and HAA is a function of the TOC and bromide concentration in the water, as well as the pH during chlorination.

Of note, Chlorate is produced as a byproduct when hypochlorite degrades during storage.

2.7.5.2 DBP Control

DBPs can be controlled by several means, including removing the DBP precursors, modifying the chlorination strategy, changing disinfectants, or removing the DBP itself. Because DBPs are difficult to remove once they are formed, control strategies typically focus on the first three methods.

Studies have shown that removal of TTHM precursors tends to remove the formation potential for the other DBPs. Generally, aggregate DBP formation will decrease as the removal of TOC increases. Recent research indicates that moving the point of chlorination back into the treatment process can reduce the formation of DBPs.

Summers et al. (1997) recently summarized the results from four studies evaluating the impact of pretreatment on DBP formation. Jar tests were conducted to simulate the water treatment through rapid mix, coagulation, flocculation, and sedimentation. Chlorine was added at various points in the jar testing to simulate the impact of various dose points on production of DBPs. The results clearly demonstrate the benefits of delaying the point of chlorination downstream in the treatment train to take advantage of precursor removal during initial flocculation and sedimentation processes. Table 2-21 summarizes the results from this study.

Table 2-21. Percent Reduction in DBP Formation by Moving Chlorination Point Later In Treatment Train

Chlorination point	TTHM Baseline (%)	TTHM Enhanced (%)	HAA5 Baseline (%)	HAA5 Enhanced (%)
Pre rapid mix	Basis	17	Basis	4.7
Post rapid mix	1.6	21	5.3	21
Mid flocculation	8.7	36	14	36
Post sedimentation	21	48	35	61

Notes: Source: USEPA, 1997b based on Summers et al., 1997.

Baseline = Baseline coagulant (alum) dose for optimal turbidity removal (~30 mg/L)

Enhanced = Enhanced coagulant (alum) dose for optimal TOC removal (~52 mg/L)

Table 2-21 also shows the benefit of enhanced coagulation to reduce DBP production. The THM reduction of 21 percent by moving the chlorination point to post sedimentation is more than doubled to 48 percent by enhanced coagulation. The HAA removal increases from 45 to 61 percent under

enhanced coagulation with post sedimentation chlorination. Therefore, DBP control by selecting the optimal dose location and conditions along with enhanced precursor removal can significantly reduce DBP formation at low added cost.

White (1992) suggested that pretreatment goals should include: 1) maximizing THM precursor removal; 2) reducing ammonia-N concentration to 0.10 mg/L; 3) reducing organic-N concentration to 0.05 mg/L; and 4) limiting 15-minute chlorine demand to 0.5 mg/L. These guidelines should improve raw water quality sufficiently to allow the use of the free chlorine residual process without exceeding the EPA MCLs for TTHMs.

2.7.6 Operational Considerations

2.7.6.1 Application Methods

Different application methods are used, depending upon the form of chlorine used. The following paragraphs describe the typical application methods for chlorine, sodium hypochlorite, and calcium hypochlorite.

Chlorine. Liquefied chlorine gas is typically evaporated to gaseous chlorine prior to metering. The heat required for evaporation can be provided through either a liquid chlorine evaporator or the ambient heat input to the storage container. Once the compressed liquid chlorine is evaporated, chlorine gas is typically fed under vacuum conditions. Either an injector or a vacuum induction mixer usually creates the required vacuum. The injector uses water flowing through a venturi to draw the chlorine gas into a side stream of carrier water to form a concentrated chlorine solution. This solution is then introduced into the process water through a diffuser or mixed with a mechanical mixer. A vacuum induction mixer uses the motive forces of the mixer to create a vacuum and draws the chlorine gas directly into the process water at the mixer.

Sodium Hypochlorite. Sodium hypochlorite solutions degrade over time. For example, a 12.5 percent hypochlorite solution will degrade to 10 percent in 30 days under “best case” conditions (White, 1992). Increased temperature, exposure to light, and contact with metals increase the rate of sodium hypochlorite degradation (Connell, 1996).

Sodium hypochlorite solution is typically fed directly into the process water using a type of metering pump. Similar to chlorine solution, sodium hypochlorite is mixed with the process water with either a mechanical mixer or induction mixer. Sodium hypochlorite solution is typically not diluted prior to mixing to reduce scaling problems.

Calcium Hypochlorite. Commercial high-level calcium hypochlorite contains at least 70% available chlorine (USEPA, 1991). Under normal storage conditions, calcium hypochlorite loses 3 to 5% of its available chlorine in a year (AWWA and ASCE, 1997). Calcium hypochlorite comes in powder, granular, and compressed tablet forms (USEPA, 1991). Typically, calcium hypochlorite solution is prepared by mixing powdered or granular calcium hypochlorite with a small flow. The highly chlorinated solution is then flow paced into drinking water flow.

2.7.6.2 Safety and Handling Considerations

Chlorine. Chlorine gas is a strong oxidizer. The U.S. Department of Transportation classifies chlorine as a poisonous gas (Connell, 1996). Fire codes typically regulate the storage and use of chlorine. In addition, facilities storing more than 2,500 pounds of chlorine are subject to the following two safety programs:

- Process Safety Management standards regulated by the Occupational Safety and Health Administration under 29 CFR 1910.
- The Risk Management Program Rule administered by EPA under Section 112(r) of the Clean Air Act.

All of these regulations (as well as local and state codes and regulations) must be considered during the design and operation of chlorination facilities at a water treatment plant.

Sodium Hypochlorite. Sodium hypochlorite solution is a corrosive liquid with an approximate pH of 12 (AWWA, 1990). Therefore, typical precautions for handling corrosive materials such as avoiding contact with metals, including stainless steel, should be used.

Sodium hypochlorite solutions may contain chlorate. Chlorate is formed during the both the manufacturing and storage of sodium hypochlorite (due to degradation of the product). Chlorate formation can be minimized by reducing the degradation of sodium hypochlorite (Gilbert et al., 1995) by limiting storage time, avoid high temperatures and reduce light exposure.

Spill containment must be provided for the sodium hypochlorite storage tanks. Typical spill containment structures include containment for the entire contents of the largest tank (plus freeboard for rainfall or fire sprinklers), no uncontrolled floor drains, and separate containment areas for each incompatible chemical.

Calcium Hypochlorite. Calcium hypochlorite is an oxidant and as such should be stored separately from organic materials that can be readily oxidized. It should also be stored away from sources of heat. Improperly stored calcium hypochlorite has caused spontaneous combustion fires (White, 1992).

2.8 Summary

2.8.1 Advantages and Disadvantages of Chlorine Use

The following list presents selected advantages and disadvantages of using chlorine as a disinfection method for drinking water (Masschelein, 1992; Process Applications, Inc., 1992). Because of the wide variation of system size, water quality, and dosages applied, some of these advantages and disadvantages may not apply to a particular system.

Advantages

- Oxidizes soluble iron, manganese, and sulfides
- Enhances color removal
- Enhances taste and odor
- May enhance coagulation and filtration of particulate contaminants
- Is an effective biocide
- Is the easiest and least expensive disinfection method, regardless of system size
- Is the most widely used disinfection method, and therefore, the best known
- Is available as calcium and sodium hypochlorite. Use of these solutions is more advantageous for smaller systems than chlorine gas because they are easier to use, are safer, and need less equipment compared to chlorine gas
- Provides a residual.

Disadvantages

- May cause a deterioration in coagulation/filtration of dissolved organic substances
- Forms halogen-substituted byproducts
- Finished water could have taste and odor problems, depending on the water quality and dosage
- Chlorine gas is a hazardous corrosive gas
- Special leak containment and scrubber facilities could be required for chlorine gas
- Typically, sodium and calcium hypochlorite are more expensive than chlorine gas
- Sodium hypochlorite degrades over time and with exposure to light
- Sodium hypochlorite is a corrosive chemical
- Calcium hypochlorite must be stored in a cool, dry place because of its reaction with moisture and heat
- A precipitate may form in a calcium hypochlorite solution because of impurities, therefore, an antiscalant chemical may be needed
- Higher concentrations of hypochlorite solutions are unstable and will produce chlorate as a byproduct
- Is less effective at high pH
- Forms oxygenated byproducts that are biodegradable and which can enhance subsequent biological growth if a chlorine residual is not maintained.

- Release of constituents bound in the distribution system (e.g., arsenic) by changing the redox state.

2.8.2 Summary Table

Table 2-22 presents a summary of the considerations for the use of chlorine as a disinfectant.

Table 2-22. Summary of Chlorine Disinfection

Consideration	Description
Generation	Chlorination may be performed using chlorine gas or other chlorinated compounds that may be in liquid or solid form. Chlorine gas can be generated by a number of processes including the electrolysis of alkaline brine or hydrochloric acid, the reaction between sodium chloride and nitric acid, or the oxidation of hydrochloric acid. Since chlorine is a stable compound, chlorine gas, sodium hypochlorite, and calcium hypochlorite are typically produced off-site by a chemical manufacturer.
Primary uses	The primary use of chlorination is disinfection. Chlorine also serves as an oxidizing agent for taste and odor control, prevention of algal growths, maintaining clear filter media, removal of iron and manganese, destruction of hydrogen sulfide, color removal, maintaining the water quality at the distribution systems, and improving coagulation.
Inactivation efficiency	The general order of increasing chlorine disinfection difficulty is bacteria, viruses, and then protozoa. Chlorine is an extremely effective disinfectant for inactivating bacteria and highly effective viricide. However, chlorine is less effective against <i>Giardia</i> cysts. <i>Cryptosporidium</i> oocysts are highly resistant to chlorine.
Byproduct formation	When added to the water, free chlorine reacts with NOM and bromide to form DBPs, primarily THMs, some haloacetic acids (HAAs), and others.
Point of application	Raw water storage, precoagulation/post-raw water storage, presedimentation/ postcoagulation, postsedimentation/prefiltration, post filtration (disinfection), or in the distribution system.
Special considerations	Because chlorine is such a strong oxidant and extremely corrosive, special storage and handling considerations should be considered in the planning of a water treatment plant. Additionally, health concerns associated with handling and use of chlorine is an important consideration.

2.8.3 Reference for Additional Information on Chlorine

With the focus of this manual on disinfectants other than chlorine, all of chlorine's uses and capabilities are not described here. For more detailed information regarding the use of chlorine in water treatment, refer to the list of references provided below. For complete references, see the References section at the end of this chapter.

- AWWA (1990)
- Connell (1996)
- DeMers and Renner (1992)
- Hazen and Sawyer (1992)
- Hoigné and Bader (1988)
- Sawyer et al. (1994)
- Singer (1988)
- White (1992)

2.9 References

1. AWWA (American Water Works Association). 1979. "Committee, Viruses in Drinking Water." *J. AWWA*. 71(8):441.
2. AWWA (American Water Works Association). 1990. *Water Quality and Treatment*. F.W. Pontius (editor). McGraw-Hill, New York, NY.
3. AWWA (American Water Works Association). 1991. *Guidance Manual for Compliance with the Filtration and Disinfection Requirements for Public Works Systems using Surface Water Sources*.
4. AWWA (American Water Works Association). 1995. *Problem Organisms in Water: Identification and Treatment*. AWWA, Denver, CO.
5. AWWA and ASCE (American Water Works Association and American Society of Civil Engineers). 1997. *Water Treatment Plant Design*. McGraw-Hill, New York, NY.
6. AWWARF (American Water Works Association Research Foundation) and Lyonnaise des Eaux. 1987. *Identification and Treatment of Tastes and Odors in Drinking Water*. American Water Works Association, Denver, CO.
7. Babcock, D.S. and P.C. Singer. 1979. "Chlorination and Coagulation of Humic and Fulvic Acids." *J. AWWA*. 71(3):149.
8. Beneson, A.S. 1981. "Control of Communicable Diseases in Man." APHA.
9. Belanger, S.E., D.S. Cherry, J.L. Farris, K.G. Sappington, and J. Cairns, Jr. 1991. "Sensitivity of the Asiatic Clam to Various Biocidal Control Agents." *J. AWWA*. 83(10):79-87.
10. Black, B.D., G.W. Harrington, and P.C. Singer. 1996. "Reducing Cancer Risks by Improving Organic Carbon Removal." *J. AWWA*. 88(6):40.

11. Brady, Thomas J., J.E. Van Benschoten, and J.N. Jensen. 1996. "Chlorination Effectiveness for Zebra and Quagga Mussels." *J. AWWA*. 88(1):107-110.
12. Britton, J.C. and B.A. Morton. 1982. "Dissection Guide, Field and Laboratory Manual for the Introduced Bivalve *Corbicula fluminea*." *Malacol. Rev.* 3(1).
13. Butterfield, C.T. et al. 1943, *Public Health Rep.* 58:1837.
14. Cameron, G.N., J.M. Symons, S.R. Spencer, and J.Y. Ma. 1989a. "Minimizing THM Formation During Control of the Asiatic Clam: A Comparison of Biocides." *J. AWWA*. 81(10):53-62.
15. Cameron, G.N., J.M. Symons, D. Bushek and R. Kulkarni. 1989b. "Effect of Temperature and pH on the Toxicity of Monochloramine to the Asiatic Clam." *J. AWWA*. 81(10):63-71.
16. CDC (Centers for Disease Control). 1989. "Assessing the Public Threat Associated with Waterborne Cryptosporidiosis: Report of a Workshop." *J. AWWA*. 80(2):88.
17. Chick, H. 1908. "Investigation of the Laws of Disinfection." *J. Hygiene*. 8:92.
18. Christman, R.F., et al. 1983. "Identity and Yields of Major Halogenated Products of Aquatic and Fulvic Acid Chlorination." *Environ. Sci. Technol.* 17(10):625.
19. Chlorine Institute. 1996. *Chlorine Institute Manual*. 6th Edition, The Chlorine Institute, Washington, D.C.
20. Clarke, N.A., et al. 1962. *Human Enteric Viruses in Water, Source, Survival, and Removability, International Conference on Water Pollution Research*. Landar.
21. Connell, G.F. 1996. *The Chlorination/Chloramination Handbook*. American Water Works Association. Denver, CO.
22. Counts, C.L. III. 1986. "The Zoogeography and History of the Invasion of the United States by *Corbicula fluminea* (Bivalvia: Corbiculidae)." *Amer. Malac. Bull.* 2(7), special edition.
23. Craun, G.F. and W. Jakubowski. 1996. "Status of Waterborne Giardiasis Outbreaks and Monitoring Methods." American Water Resources Association, Water Related Health Issue Symp., Atlanta, GA. November.
24. Craun, G.F. 1981. "Outbreaks of Waterborne Disease in the United States." *J. AWWA*. 73(7):360.
25. Culp, G.L., and R.L. Culp. 1974. *New Concepts in Water Purification*. Van Nostrand Reinhold Company, New York, NY.

26. Culp/Wesner/Culp. 1986. *Handbook of Public Water Systems*. Van Nostrand Reinhold, New York, NY.
27. DeMers, L.D. and R.C. Renner, R.C. 1992. "Alternative Disinfection Technologies for Small Drinking Water Systems." AWWA and AWWARF, Denver, CO.
28. Duguet, J.P., Y. Tsutsumi, A. Bruchet, and Mallevalle. 1985. "Chloropicrin in Potable Water: Conditions of Formation and Production during Treatment Processes." *Water Chlorination: Chemistry, Environmental Impact and Health Effects*, Volume 5. Lewis Publishers.
29. Evans, L.P., Jr., et al. 1979. Salinity Relationships in *Corbicula fluminea*; *Miller (1774)*. Conference proceedings, first International Corbicula Symposium. J.C. Britton (editor). Texas Christian Univ., Ft. Worth, TX.
30. Farvardin, M.R. and A.G. Collins. 1990. Mechanism(s) of Ozone-Induced Coagulation of Organic Colloids. Conference Proceedings, AWWA Annual Conference, Cincinnati, OH. June 17-21.
31. Ferguson, D.W., J.T. Gramith, and M.J. McGuire. 1991. "Applying Ozone for Organics Control and Disinfection: A Utility Perspective." *J. AWWA*. 83(5):32-39.
32. Ferguson, D.W., M.J. McGuire, B. Koch, R.L. Wolfe, and E.M. Aieta. 1990. "Comparing PEROXONE and Ozone for Controlling Taste and Odor Compounds, Disinfection Byproducts, and Microorganisms." *J. AWWA*. 82(4):181-191.
33. Finch, G.R., E.K. Black, and L.L. Gyürék. 1994. Ozone and Chlorine Inactivation of *Cryptosporidium*. Conference proceedings, Water Quality Technology Conference, Part II. San Francisco, CA.
34. Geldreich, E.E. 1972. *Water Pollution Microbiology*. R. Mitchell (editor). John Wiley & Sons, New York, NY.
35. Gordon, G., L. Adam, and B. Bubnis. 1995. *Minimizing Chlorate Ion Formation in Drinking Water when Hypochlorite Ion is the Chlorinating Agent*. AWWA-AWWARF, Denver, CO.
36. Gurol, M.D. and M. Pidotella. 1983. A Study of Ozone-Induced Coagulation. Conference proceedings, ASCE Environmental Engineering Division Specialty Conference. Allen Medine and Michael Anderson (editors). Boulder, CO.
37. Gyürék, L.L., L.R.J. Liyanage, M. Belosevic, and G.R. Finch. 1996. "Disinfection of *Cryptosporidium Parvum* Using Single and Sequential Application of Ozone and Chlorine Species." Conference proceedings, AWWA Water Quality Technology Conference, Boston, MA.

38. Haas C.N. and R.S. Engelbrecht. 1980. "Physiological Alterations of Vegetative Microorganisms Resulting from Aqueous Chlorination." *J. Water Pollution Control Fed.* 52(7):1976.
39. Hazen and Sawyer. 1992. *Disinfection Alternatives for Safe Drinking Water.* Van Nostrand Reinhold, New York, NY.
40. Herbert, P.D.N., B.W. Muncaster II, and G.L. Mackie. 1989. "Ecological and Genetic Studies on *Dreissena polymorpha* (Pallas): A New Mollusc in the Great Lakes." *Can. Jour. Fisheries and Aquatic Sci.* 46:1587.
41. Hildebrand, D.J., A.F. Hess, P.B. Galant, and C.R. O'Melia. 1986. "Impact of Chlorine Dioxide and Ozone Preoxidation on Conventional Treatment and Direct Filtration Treatment Processes." Conference proceedings, AWWA Annual Conference, Denver, CO.
42. Hoff, J.C., E.W. Rice, and F.W. Schaefer. 1984. "Disinfection and the Control of Waterborne Giardiasis." Conference proceedings, ASCE Specialty Conference.
43. Hoigné J., and H. Bader. 1988. "The Formation of Trichloronitromethane (chloropicrin) and Chloroform in a Combined Ozonation/Chlorination Treatment of Drinking Water." *Water Resources.* 22 (3):313.
44. Huck, P.M., W.B. Anderson, C.L. Lang, W.A. Anderson, J.C. Fraser, S.Y. Jasim, S.A. Andrews, and G. Pereira. 1995. "Ozone vs. PEROXONE for Geosmin and 2-Methylisoborneol Control: Laboratory, Pilot and Modeling Studies." Conference proceedings, AWWA Annual Conference, Anaheim, CA.
45. IOA. 1997. IOA Survey of Water Treatment Plants. International Ozone Association, Stanford, CT.
46. Karimi, A.A. and P.C. Singer. 1991. Trihalomethane Formation in Open Reservoirs. *J. AWWA.* 83 (3):84.
47. Klerks, P.L. and P.C. Fraleigh, P.C. 1991. "Controlling Adult Zebra Mussels with Oxidants." *J. AWWA.* 83 (12):92-100.
48. Koch, B., S.W. Krasner, M.J. Scimienti, and W.K. Schimpff. 1991. "Predicting the Formation of DBPs by the Simulated Distribution System." *J. AWWA.* 83(10):62-70.
49. Kramer, M.H., B.L. Herwaldt, G.F. Craun, R.L. Calderon, and D.D. Juranek. 1996. "Waterborne Disease: 1993 and 1994." *J. AWWA.* 88(3):66-80.
50. Krasner, S.W., M.J. McGuire, J.G. Jacangelo. 1989. "The Occurrence of Disinfection Byproducts in US Drinking Water." *J. AWWA.* 81(8):41-53.

51. Lâiné, J.M., J.G. Jacangelo, E.W. Cummings, K.E. Carns, J. Mallevalle. 1993. "Influence of Bromide on Low-Pressure Membrane Filtration for Controlling DBPs in Surface Waters." *J. AWWA*. 85(6):87-99.
52. Lalezary, S., M. Pirbazari, and M.J. McGuire. 1986. "Oxidation of Five Earthy-Musty Taste and Odor Compounds." *J. AWWA*. 78(3):62.
53. Lang, C.L. 1994. "The Impact of the Freshwater Macrofouling Zebra Mussel (*Dreissena Polymorpha*) on Drinking Water Suppliers." Conference proceedings, AWWA Water Quality Technology Conference Part II, San Francisco, CA.
54. Langlais, B., D.A. Reckhow, and D.R. Brink. (editors). 1991. *Ozone in Drinking Water Treatment: Application and Engineering*. AWWARF and Lewis Publishing, Chelsea, MI.
55. Liu, O.C., et al. 1971. "Relative Resistance of Twenty Human Enteric Viruses to Free Chlorine. Virus and Water Quality: Occurrence and Control." Conference Proceedings, thirteenth Water Quality Conference, University of Illinois, Urbana-Champaign.
56. MacKenzie, W.R., et al. 1994. "A Massive Outbreak in Milwaukee of *Cryptosporidium* Infection Transmitted Through the Public Water Supply." *New England J. of Medicine*. 331(3):161.
57. Masschelein, W.J. 1992. "Unit Processes in Drinking Water Treatment." Marcel Decker D.C., New York, Brussels, Hong Kong.
58. Matisoff, G., G. Brooks, and B.I. Bourland. 1996. "Toxicity of Chlorine Dioxide to Adult Zebra Mussels." *J. AWWA*. 88 (8):93-106.
59. McGuire, M.J., and R.G. Meadow. 1989. "AWWARF Trihalomethane Survey." *J. AWWA*. 80(1):61.
60. Montgomery J. M. 1985. *Water Treatment Principles and Design*. John Wiley & Sons, New York, NY.
61. Nieminski, E.C., S. Chaudhuri, and T. Lamoreaux. 1993. "The Occurrence of DBPs in Utah Drinking Waters." *J. AWWA*. 85(9):98-105.
62. Oliver, B.G., and D.B. Shindler. 1980. "Trihalomethanes From Chlorination of Aquatic Algae." *Env. Sci. Tech.* 14(12):1502.
63. Olson, K.E. 1982. An Evaluation of Low Chlorine Concentrations on *Giardia* Cyst Viability, USDA Forest Service, Equipment Development Center, San Dimas, CA. January.

64. Pourmoghaddas, H., A.A. Stevens, R.N. Kinman, R.C. Dressman, L.A. Moore, J.C. Ireland. 1993. "Effect of Bromide Ion on Formation of HAAs During Chlorination." *J. AWWA*. 85(1):82-87.
65. Prendiville, P.W. 1986. "Ozonation at the 900 cfs Los Angeles Water Purification Plant." *Ozone: Sci. Engrg.* 8:77.
66. Reckhow D.A., W.R. Knocke, M.J. Kearney, C.A. Parks. 1991. "Oxidation of Iron and Manganese by Ozonation." *Environ. Sci. and Engrg.* 13(6):675-695.
67. Reckhow D.A., P.C. Singer, and R.L. Malcolm. 1990. "Chlorination of Humic Materials: Byproduct Formation and Chemical Interpretations." *Environ. Sci. Technol.* 24(11):1655.
68. Reckhow, D.A., and P.C. Singer. 1985. "Mechanisms of Organic Halide Formation During Fulvic Acid Chlorination and Implications with Respect to Preozonation." *Water Chlorination: Chemistry, Environmental Impact and Health Effects*, Volume 5. Jolley, R.L. et al. (editors). Lewis Publishers, Chelsea, MI.
69. Reckhow, D.A., J.K. Edzwald, and J.E. Tobiason. 1993. *Ozone as an Aid to Coagulation and Filtration*. AWWARF, AWWA, Denver, CO.
70. Reckhow, D.A., P.C. Singer, and R.R. Trussell. 1986. Ozone as a coagulant aid. Seminar proceedings, Ozonation, Recent Advances and Research Needs, AWWA Annual Conference, Denver, CO.
71. Rice, R.G., Overbeck, P.K., Larson, K. 1998. Ozone Treatment for Small Water Systems. Presented at First International Symposium on Safe Drinking Water in Small Systems, NSF International/PAHP/WHO, Arlington, VA. (In press)
72. Riggs, J.L. 1989. "Aids Transmission in Drinking Water: No Threat." *J. AWWA*. 81(9):69.
73. Roberts, R. 1990. "Zebra Mussel Invasion Threatens US Waters." *Science*. 249:1370.
74. Salvato, J.A., Jr. 1972. *Environmental Engineering and Sanitation*. second edition, John Wiley & Sons, New York, NY.
75. Sawyer, C.N., P.L. McCarty, L. Parkin, and G.F. Parkin. 1994. *Chemistry for Environmental Engineering*. McGraw Hill, Inc., New York, NY.
76. Scarpino P.V., et al. 1972. "A Comparative Study of the Inactivation of Viruses in Water by Chlorine." *Water Research*. 6:959.
77. Sinclair, R.M. 1964. "Clam Pests in Tennessee Water Supplies." *J. AWWA*. 56 (5):592.

78. Singer, P.C. 1988. *Alternative Oxidant and Disinfectant Treatment Strategies for Controlling THM Formation*. EPA 600/S2-88/044. October.
79. Singer P.C. 1992. "Formation and Characterization of Disinfection Byproducts." Presented at the First International Conference on the Safety of Water Disinfection: Balancing Chemical and Microbial Risks.
80. Singer P.C. 1993. "Trihalomethanes and Other Byproducts Formed From the Chlorination of Drinking Water." National Academy of Engineering Symposium on Environmental Regulation: Accommodating Changes in Scientific, Technical, or Economic Information. Washington, D.C.
81. Singer P.C., and S.D. Chang. 1989. "Correlations Between Trihalomethanes and Total Organic Halides Formed During Water Treatment." *J. AWWA*. 81(8):61-65.
82. Singer P.C., and G.W. Harrington. 1993. "Coagulation of DBP Precursors: Theoretical and Practical Considerations." Conference proceedings, AWWA Water Quality Technology Conference, Miami, FL.
83. Smith, A.L. et al. 1979. "Clams--A growing Threat to Implant Water Systems." *Plant Engrg.* 33:165.
84. Snead, M.C., et al. 1980. *Benefits of Maintaining a Chlorine Residual in Water Supply Systems*. EPA 600/2-80-010.
85. Stevens, A.A., et al. 1976. "Chlorination of Organics in Drinking Water." *J. AWWA*. 8(11):615.
86. Stevens, A.A., L.A. Moore, R.J. Miltner. 1989. "Formation and Control of Non-Trihalomethane Disinfection By-products." *J. AWWA*. 81(8):54-60.
87. Suffet, I. H., C. Anselme, and J. Mallevalle. 1986. "Removal of Tastes and Odors by Ozonation." Conference proceedings, AWWA Seminar on Ozonation: Recent Advances and Research Needs, Denver, CO.
88. Summers, R.S., G. Solarik, V.A. Hatcher, R.S. Isabel, J.F. Stile. 1997. "Analyzing the Impacts of Predisinfection Through Jar Testing." Conference proceedings, AWWA Water Quality Technology Conference, Denver, CO.
89. Taylor, F.B. 1974. "Viruses - What is Their Significance in Water Supplies." *J. AWWA*. 66:306.
90. Thibaud, H., H. DeLaat, N. Merlet, and M. Doré. 1987. "Chloropicrin Formation in Aqueous Solution: Effect of Nitrites on Precursors Formation During the Oxidation of Organic Compounds." *Water Res.* 21(7):813.

91. Thibaud, H., J. DeLaat, and M. Doré. 1988. "Effects of Bromide Concentration on the Production of Chloropicrin During Chlorination of Surface Waters: Formation of Brominated Trihalonitromethanes." *Water Res.* 22(3):381.
92. Tobiason, J.E., J.K. Edzwald, O.D. Schneider, M.B. Fox, and H.J. Dunn. 1992. "Pilot Study of the Effects of Ozone and PEROXONE on In-Line Direct Filtration." *J. AWWA.* 84(12):72-84.
93. USEPA. 1998a. *Occurrence Assessment for Disinfectants and Disinfection Byproducts in Public Drinking Water Supplies.* Science Applications International Corporation under contract for Office of Ground Water and Drinking Water. Washington, DC.
94. USEPA. 1998b. *Technologies and Costs for Control of Disinfection Byproducts.* Prepared by Malcolm Pirnie, Inc for U.S. Environmental Protection Agency, Office of Ground Water and Drinking Water, PB93-162998.
95. USEPA. 1997a. *Community Water System Survey - Volumes I and II; Overview.* EPA 815-R-97-001a, -001b. January.
96. USEPA. 1997b. "National Primary Drinking Water Regulations: Disinfectants and Disinfection Byproducts; Notice of Data Availability; Proposed Rule." *Federal Register.* 62(212):59387-59484. November 3.
97. USEPA. 1996. *Drinking Water Regulations and Health Advisories.* EPA 822-B-96-002, October.
98. USEPA. 1991. *Manual of Individual and Non-Public Works Supply Systems.* Office of Water, EPA 570/9-91-004.
99. Van Benschoten, J.E., J.N. Jensen, D. Harrington, and D.J. DeGirolamo. 1995. "Zebra Mussel Mortality With Chlorine." *J. AWWA.* 87(5):101-108.
100. Wachter, J.K., and J.B. Andelman. 1984. "Organohalide Formation on Chlorination of Algal Extracellular Products." *Env. Sci. Technol.* 18(11):811.
101. Watson, H.E. 1908. "A Note on the Variation of the Rate of Disinfection With Change in the Concentration of the Disinfectant." *J. Hygiene.* 8:538.
102. White, G.C. 1992. *Handbook of Chlorination and Alternative Disinfectants.* Van Nostrand Reinhold, New York, NY.
103. Witherell, L.E, R.W. Duncan, K.M. Stone, L.J. Stratton, L. Orciari, S. Kappel, D.A. Jillson. 1988. "Investigation of Legionella Pneumophila in Drinking Water." *J. AWWA.* 80 (2):88-93.

DISINFECTANT USE IN WATER TREATMENT	2-1
2.1 NEED FOR DISINFECTION IN WATER TREATMENT.....	2-1
2.1.1 Pathogens of Primary Concern.....	2-2
2.1.2 Recent Waterborne Outbreaks	2-8
2.1.3 Mechanism of Pathogen Inactivation	2-9
2.2 OTHER USES OF DISINFECTANTS IN WATER TREATMENT	2-10
2.2.1 Minimization of DBP Formation.....	2-10
2.2.2 Control of Nuisance Asiatic Clams and Zebra Mussels.....	2-11
2.2.3 Oxidation of Iron and Manganese	2-13
2.2.4 Prevention of Regrowth in the Distribution System and Maintenance of Biological Stability.....	2-14
2.2.5 Removal of Taste and Odors Through Chemical Oxidation	2-15
2.2.6 Improvement of Coagulation and Filtration Efficiency	2-15
2.2.7 Prevention of Algal Growth in Sedimentation Basins and Filters	2-16
2.2.8 Removal of Color	2-16
2.3 DISINFECTION BYPRODUCTS AND DISINFECTION RESIDUALS	2-16
2.3.1 Types of DBPs and Disinfection Residuals	2-16
2.3.2 Disinfection Byproduct Formation	2-19
2.3.3 DBP Control Strategies.....	2-23
2.3.4 CT Factor	2-25
2.4 PATHOGEN INACTIVATION VERSUS DBP FORMATION	2-26
2.5 DISINFECTANT RESIDUAL REGULATORY REQUIREMENTS	2-27
2.6 SUMMARY OF CURRENT NATIONAL DISINFECTION PRACTICES	2-28
2.7 CHLORINE	2-30
2.7.1 Chlorine Chemistry	2-31
2.7.2 Chlorine Generation	2-32
2.7.3 Primary Uses and Points of Application of Chlorine.....	2-33
2.7.4 Pathogen Inactivation and Disinfection Efficacy.....	2-35
2.7.5 DBP Formation and Control	2-39
2.7.6 Operational Considerations.....	2-41
2.8 SUMMARY	2-42
2.8.1 Advantages and Disadvantages of Chlorine Use.....	2-42
2.8.2 Summary Table	2-44
2.8.3 Reference for Additional Information on Chlorine	2-44
2.9 REFERENCES	2-45

Table 2-1. Waterborne Diseases from Bacteria.....	2-3
Table 2-2. Waterborne Diseases from Human Enteric Viruses.....	2-4
Table 2-3. Waterborne Diseases from Parasites.....	2-6
Table 2-4. Attributes of the Three Waterborne Pathogens of Concern in Water Treatment.....	2-7
Table 2-5. Human Parasitic Protozoans.....	2-7
Table 2-6. The Effects of Various Oxidants on Mortality of the Asiatic Clam (<i>Corbicula fluminea</i>).....	2-12
Table 2-7. Oxidant Doses Required for Oxidation of Iron and Manganese.....	2-14
Table 2-8. List of Disinfection Byproducts and Disinfection Residuals.....	2-17
Table 2-9. Status of Health Information for Disinfectants and DBPs.....	2-18
Table 2-10. Conditions of Formation of DBPs	2-22
Table 2-11. Inorganic DBPs Produced During Disinfection.....	2-23
Table 2-12. Required Removal of TOC by Enhanced Coagulation for Surface Water Systems ⁺ Using Conventional Treatment ⁺⁺ (percent reduction).....	2-25
Table 2-13. CT Values for Inactivation of Viruses	2-26
Table 2-14. CT Values for Inactivation of <i>Giardia</i> Cysts.....	2-26
Table 2-15. Summary of Disinfection Impacts	2-27

Table 2-16. Disinfection Practices of Water Systems that Include Some Form of Treatment. 2-29

Table 2-17. Ozone Application in Water Treatment Plants in the United States 2-30

Table 2-18. Chlorine Uses and Doses..... 2-34

Table 2-19. Typical Chlorine Points of Application and Uses 2-34

Table 2-20. Typical Chlorine Dosages at Water Treatment Plants..... 2-35

Table 2-21. Percent Reduction in DBP Formation by Moving Chlorination Point Later In Treatment Train 2-40

Table 2-22. Summary of Chlorine Disinfection 2-44

Figure 2-1. Free Chlorine *Giardia* and Virus CT Requirements 2-38

Figure 2-2. CT Values for Inactivation of *Giardia* Cysts by Free Chlorine at 10°C (at Cl₂ dose of 3.0 mg/L)..... 2-38

Figure 2-3. CT Values for Inactivation of *Giardia* Cysts by Free Chlorine at pH 7.0 (at Cl₂ dose of 3.0 mg/L)... 2-39