Manitoba Water
Stewardship

Chlorine and Alternative Disinfectants
Guidance Manual

Prepared for
Office of Drinking Water
Prepared by
Earth Tech (Canada) Inc.

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Manitoba
Building for the Future

Chlorine and Alternative Disinfectants Guidance Manual

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CHLORINE AND ALTERNATIVE DISINFECTANTS GUIDANCE MANUAL

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LIST OF SYMBOLS, UNITS AND ABBREVIATIONS

A_{254}	Absorbance at 254 nm wavelength
AOC	Assimilable organic carbon
BrO_3-	Bromate ion
°C	Degrees Celsius
C	Disinfectant concentration (mg/L)
Ca^+	Calcium ion
$Ca(OCl)_2$	Calcium hypochlorite
CDBPs	Chlorinated disinfection by-products
CDHS	California Department of Health Services
CFD	Computational fluid dynamics
Cl^-	Chloride ion
Cl_2	Free chlorine
ClO_2	Chlorine dioxide
ClO_3^-	Chlorate ion
CT	Product of disinfectant residual concentration and effective disinfectant contact time (mg·min/L)
D	UV dose (mW-s/cm^2)
DBPs	Disinfection by-products
DBPFP	Disinfection by-products formation potential
DNA	Deoxyribonucleic acid
GAC	Granular activated carbon
GUDI	Groundwater under the direct influence of surface water
H^+	Hydrogen ion
HAA_5s	Haloacetic acids
HCl	Hydrochloric acid

H_2O	Water
$HOCl$	Hypochlorous acid
HPC	Heterotrophic Plate Count
I	Average intensity (mW/cm^2)
k	Microorganisms reduction constant
log N/N$_o$	Log reduction of microorganisms
LPHI	Low pressure high intensity
LT2ESWTR	Long Term 2 Enhanced Surface Water Treatment Rule
IMAC	Interim Maximum Acceptable Concentration
mg·min/L	Unit of CT product
MPHI	Medium pressure high intensity
N	Microorganism concentration after inactivation
N$_0$	Microorganism concentration before inactivation
Na^+	Sodium ion
NA	Not applicable
$NaCl$	Sodium chloride
$NaClO_2$	Sodium chlorite
$NaOCl$	Sodium hypochlorite
$NaOH$	Sodium hydroxide
NCl_3	Nitrogen trichloride
ND	Not detectable
$NDMA$	N-nitrosodimethylamine
NH_3	Ammonia
NH_2Cl	Monochloramine
$NHCl_2$	Dichloramine
NOM	Natural organic matter
NTU	Nephelometric Turbidity Unit

O_3	Ozone
OCl^-	Hypochlorite ion
ODW	Office of Drinking Water
OH^-	Hydroxide ion
OSHA	Occupational Safety and Health Administration
PAC	Powdered activated carbon
PLC	Programmable logic controller
PVC	Polyvinyl chloride
RNA	Ribonucleic acid
SCBA	Self-contained breathing apparatus
SDS	Simulated distribution system
t	Exposure time (seconds)
T_{10}	Length of time during which not more than 10% of the influent water would pass through the process
TCU	True colour unit
TDS	Total dissolved solids (mg/L)
THMs	Trihalomethanes
TOC	Total organic carbon (mg/L)
USEPA	United States Environmental Protection Agency
UV	Ultraviolet light
WHO	World Health Organization
XDBPs	Halogenated disinfection by-products

EXECUTIVE SUMMARY

In drinking water treatment, chlorination has historically been used as a stand-alone disinfectant. However, water disinfection has evolved from simple and effective chlorination to include alternative or advanced systems like chloramines, ozone, chlorine dioxide and ultraviolet radiation. At the same time there are concerns due to long-term health risks caused by the formation of disinfection by-products (DBPs). The basic objective of this manual is to provide a general guideline for the selection and application of the most appropriate disinfectants for both small and large drinking water systems in Manitoba. Each of the disinfectants was evaluated and compared against each other. Various decision-making flowcharts were developed for determining the most appropriate disinfectants for both small and large drinking water systems. The manual also provides general guidance for proponents to obtain approval for utilization of alternative disinfectants and summarizes the best practices for each of the options. A detailed discussion on each of the disinfectants is presented, based on the following categories: disinfection effectiveness, design criteria, operational requirements, maintenance issues, monitoring requirements, and safety considerations. Water systems in Manitoba should use this document for gaining general information about disinfectants and their suitability as disinfectants for use in their own water systems.

SECTION 1.0
INTRODUCTION

1.1   GENERAL

Chlorine is the most widely used disinfectant in North America. Few questions were asked about the efficacy of chlorination, due to its success in water disinfection in the early part of the last century. However, over the last few decades there were new challenges in water treatment because of increased presence or emergence of waterborne pathogens like *Giardia* and *Cryptosporidium*. At the same time establishment of the possible link between halogenated disinfection-by-products (DBPs) caused by chlorination and cancer have prompted many water systems to look for alternatives. Some of these alternatives are chloramines, ozone, chlorine dioxide and ultraviolet light.

This report focuses on the disinfectants that may be applied in drinking water treatment, their typical uses, advantages and disadvantages. It describes the key decision-making criteria to be used in identifying feasible options of disinfection for both small and large drinking water systems. It provides general guidance for proponents to obtain approval for utilization of alternative disinfectants and also summarizes the best practices for each of the disinfection options.

1.2   OBJECTIVE

This manual neither recommends nor advocates water systems to switch from their current method of disinfection to the alternative disinfection methods, or add an additional disinfection process discussed in this manual. The decision to change disinfection methods depends upon a number of factors, which may require a thorough evaluation of site-specific conditions. This manual is for information purposes only. It provides general guidelines for the selection and application of the most appropriate disinfectant or combination of disinfectants for both small and large drinking water systems in Manitoba.

The specific objectives of this guideline are as follows:
- Development of a decision-making matrix for selection of appropriate disinfectants
- Listing of best practices related to design, operation, maintenance, and monitoring
- Presentation of the provincial approval process for alternative disinfectants
- Presentation of requirements for small drinking water systems if different from the overall approach
- Listing of applicable reference documents

SECTION 2.0
LITERATURE REVIEW

2.1   CANADA

In Canada, the delivery of drinking water is primarily the responsibility of the provinces and municipalities. The Federal-Provincial Subcommittee for Drinking Water establishes guidelines for drinking water quality in collaboration with the health and environment ministries of the provinces and territories. The "*Guidelines for Canadian Drinking Water Quality*" (Federal-Provincial Committee on Drinking Water) lists most of the substances that have been found in drinking water and are known or suspected to be harmful. Provinces and Territories develop their own guidelines and legislation based on this document though not all use this as a benchmark.

2.1.1   Alberta

In Alberta, the guidelines for drinking water quality were developed by Alberta Environmental Protection (AEP). The AEP considers the establishment of standards and guidelines for municipal waterworks an integral part of their regulatory program to ensure public health and environment protection. In Alberta, waterworks systems in accordance with the Potable Water Regulation (122/93) must be designed so that they meet the standards and design requirements set out in the latest edition of the "*Standards and Guidelines for Municipal Waterworks, Wastewater, and Storm Drainage Systems*", published by the AEP, or any other standards and design requirements specified by the Director. The manual provides guidelines for alternative disinfectants such as chloramines, ozone, and chlorine dioxide (AEP 1997). The manual provides detailed performance requirements for treatment with respect to the required bacteria, *Giardia* and virus removal, typical baffling conditions, and reporting requirements.

The guidelines have four primary sections, which are as follows (AEP 1997):

a) Performance Standards: These are either narrative criteria or numerical limits on residual disinfectant concentrations, which are mandatory requirements for water systems.

b) Design Standards: These are minimum standards for design, construction, and operation of water systems that ensure a particular environmental quality or public health objective. Standards include disinfection requirements, required *Giardia* or virus removal, typical baffling conditions, and calculation and reporting data.

c) Design Guidelines: These are general guidelines on how to achieve a certain level of system reliability and performance and are not mandatory requirements.

d) Operating and Monitoring Requirements and Guidelines: These are system operation, monitoring and reporting requirements and guidelines that are essential to ensure sustainable production and delivery of high quality water.

2.1.2 British Columbia

The British Columbia Water Quality Guidelines (Criteria) Report developed by the Ministry of Water, Land and Air Protection lists guidelines for both drinking water and surface water protection (MWLAP 1998). The British Columbia Water Quality Guidelines (Criteria) Report is revised periodically to incorporate new information. The latest and amended Drinking Water Protection Act and regulations came into force on May 16, 2003, replacing the Safe Drinking Water Regulation under the Health Act. Currently they do not have any requirements for the implementation of alternative disinfectants.

2.1.3 Ontario

In Ontario, the *Safe Drinking Water Act* and its regulations apply to drinking water systems. The regulations set out treatment and testing requirements for all categories of regulated water systems, including small non-municipal and seasonal operations. The *Procedure for Disinfection of Drinking Water in Ontario* (MOE 2003) is a supporting document specific to water disinfection and any pre-disinfection processes that may be necessary to ensure the effectiveness of disinfection. In general, it recommends the design and construction of both primary and secondary disinfection facilities as laid out in the *Recommended Standards for Water Works* (GLUMRB 2003) or the *Ten State Standards*. The document provides guidance for both primary and secondary disinfection necessary to achieve the required level of removal or inactivation of pathogens potentially present in the source water. It also provides guidance for the control of disinfection-by-products and disinfection procedures following drinking water system construction and repair. The document provides guidelines for the application of alternative disinfectants such as chloramines, chlorine dioxide, ozone, and UV. The document also provides disinfection requirements for specific values of log inactivation of *Giardia* cysts and target viruses (hepatitis A) at specific temperatures and pH levels. One of the significant developments in the guideline is that the province now regulates *Cryptosporidium*. The *CT* tables were based on the *USEPA Guidance Manual for Compliance with the Filtration and Disinfection Requirements for Public Water Systems Using Surface Water Sources* (USEPA 1991).

2.1.4 Saskatchewan

In Saskatchewan, drinking water regulations and guidelines are controlled by Saskatchewan Environment. *A Guide to Waterworks Design* (Saskatchewan Environment 2002) published by Saskatchewan Environment addresses the design of water treatment units so as to safeguard the public and protect the environment. For private and municipal designers and waterworks owners, the guidelines identify factors that should be considered for waterworks and provide accepted practices in Saskatchewan conditions. The document includes general guidance about disinfectants (chlorine, chloramines, chlorine dioxide, and ozone) in drinking water

based on USEPA guidelines to be used for effective disinfection (Saskatchewan Environment 2002).

2.1.5 Manitoba

In Manitoba, the Office of Drinking Water was established for the assessment of water infrastructure, monitoring of water plants and operators, and to provide assistance to water system owners and operators.

The Office of Drinking Water applies the *Recommended Standards for Water Works* (GLUMRB 2003) or the *Ten State Standards* developed by the Great Lakes - Upper Mississippi River Board of State and Provincial Public Health and Environmental Managers for water system design, AWWA standards, and best practices.

On January 20, 2004, Manitoba's new Drinking Water Safety Act was proclaimed into law. The first two regulations brought forward under this Act are:

- *The Drinking Water Standards Regulation*, which regulates the quality of water being provided to Manitobans.
- *The Drinking Water Safety Regulation*, which regulates the design, construction and operation of water supply infrastructure.

2.2 UNITED STATES

2.2.1 USEPA

The United States Environmental Protection Agency (USEPA) is the principle governing body in setting drinking water treatment standards and guidelines in the United States. Under the authority of the Safe Drinking Water Act (SDWA), the USEPA sets standards for approximately 90 contaminants in drinking water. For each of these contaminants, USEPA sets a legal limit, called a maximum contaminant level, or requires a certain level of treatment. Water suppliers are not allowed to provide water that does not meet these standards. The Alternative Disinfectants and Oxidants Guidance Manual (USEPA 1999) developed by the USEPA provides technical data and engineering information on alternative disinfectants such as chloramines, ozone, chlorine dioxide and UV. It provides a discussion of the background and regulatory context of alternative disinfectants and a decision-making framework that water systems can employ to assess the applicability of various disinfectants and disinfection strategies for individual systems (USEPA 1999). The USEPA is currently developing the Long Term 2 Enhanced Surface Water Treatment Rule (LT2ESWTR) to reduce the risk of *Cryptosporidium* and other microbial pathogens in drinking water. In June 2003, the USEPA released the draft of the LT2ESWTR Toolbox Guidance Manual (USEPA 2003a). The purpose of the toolbox is solely to provide technical information on applying *Cryptosporidium* treatment and management strategies that are part of the upcoming LT2ESWTR. The draft discusses the applicability of alternative disinfectants in achieving its goal.

In June 2003, USEPA released the draft of the Ultraviolet Disinfection Guidance Manual. The purpose of this guidance manual is solely to provide technical information on the application of ultraviolet light for the disinfection of drinking water by public water systems for compliance with the LT2ESWTR. It provides guidance and the necessary tools to assess UV installations at the design, start-up, and routine operation phases.

2.2.2 Ten State Standards

The Great Lakes-Upper Mississippi River Board of State and Provincial Public Health and Environmental Managers (GLUMRB) established in 1950 created a Water Supply Committee consisting of one associate from each of the ten states in the Great Lakes-Upper Mississippi River area and the Province of Ontario, Canada (GLUMRB 2003). The GLUMRB publishes the guidance manual "*Recommended Standards for Water Works*" and updates it periodically with the advancement of technology. The 2003 edition of the guidance manual consists of policy statements, interim standards and recommended standards for waterworks operations. Among the disinfectants, standards and recommendations are provided for chlorine, ozone, chlorine dioxide, and ultraviolet light.

2.3 WORLD HEALTH ORGANIZATION

The World Health Organization publishes the *WHO Guidelines for Drinking-Water Quality* and is kept up-to-date in a series of rolling revisions (WHO 1997). The Guidelines are designed for use by water and health regulators, policy makers, and their advisors; in the development of national standards. The Guidelines and their associated documents are also used by many others as a source of information on water quality and health and on effective management approaches. The manual provides information about alternative and advanced disinfection processes used in water treatment. It also provides ranking of technical complexities among the different disinfection methods.

2.4 AUSTRALIA AND NEW ZEALAND

The *Australian Drinking Water Quality Guidelines* (NHMRC 1996) were prepared by a joint committee of the Agricultural and Resource Management Council of Australia and New Zealand, and the National Health and Medical Research Councils. The guidelines provide an authoritative Australian reference, which provide the Australian community and the water supply industry with guidance on what constitutes good quality drinking water. The guideline values in this manual were based primarily on the recommendations by the World Health Organization (WHO). The guideline manual discusses comprehensively all alternative disinfectants like chloramines, chlorine dioxide, ozone, ultraviolet irradiation, and other disinfectants (NHMRC 1996). It describes in detail the disinfection effectiveness and monitoring requirements both for small and large drinking water systems.

SECTION 3.0
DISINFECTANT SELECTION

3.1 DISINFECTANTS IN WATER TREATMENT

3.1.1 Chlorine

Chlorine is still the most widely used disinfectant in North America. It is very effective against a wide range of pathogens including bacteria and viruses. Chlorine is stable and it is capable of providing the necessary residual protection in the distribution system. Chlorination is also a highly economical process.

Chlorination has several disadvantages as well. As a disinfectant, it is not effective against protozoan oocysts like *Cryptosporidium*. Chlorine reacts with natural organic matter in water and forms halogenated by-products, which can cause long-term health effects. Application of gaseous chlorine in water is a hazardous process requiring special safety measures. High doses of chlorine can also cause taste and odour problems. Chlorine at a lower concentration is commonly used as a secondary disinfectant in most water systems in order to provide residual protection in the distribution system.

3.1.2 Chloramines

Chloramines are formed by the reaction of free chlorine and ammonia. They are more stable than free chlorine and are very effective for providing residual protection in the distribution system. They also form fewer halogenated by-products as compared to chlorine.

Monochloramine is the preferred chloramine species for use in water treatment because it causes less taste and odour problems compared to the other chloramines species. Monochloramine residual is very effective in controlling biofilms, which reduces coliform concentrations and corrosion in the distribution system. The normal dosage range for monochloramine is in the range of 1.0 to 4.0 mg/L (USEPA 1999). Excess ammonia used during the chloramination process in water treatment may cause nitrification. Nitrification can have an adverse effect on water quality such as the loss of total chlorine, excess ammonia residuals and an increase in bacteria concentration.

The germicidal effectiveness of monochloramine is significantly less than that of free chlorine. Monochloramine is generally not used as a primary disinfectant as it is weak in the inactivation of viruses and protozoa. Its effectiveness against *Cryptosporidium* is not practically feasible. However, monochloramine is a good choice for secondary disinfection because of its stability and persistence, and because it generally produces significantly lower levels of DBPs. It can provide the necessary residual protection in the distribution system.

3.1.3   Ozone

Ozone was first used for drinking water disinfection in Europe in the late 19th century. It took several years for ozone to transfer to North America for the purpose of water disinfection. Early application of ozone in North America was primarily for colour removal and taste or odour control. Due to its powerful oxidizing ability, ozone gained popularity significantly in the late 20th century.

Ozone is a powerful disinfectant, which is able to achieve effective disinfection with less contact time and concentration. Several studies have demonstrated that ozone has high germicidal effectiveness against bacteria, viruses, and protozoan cysts. However, because of its short half-life ozone can only be used as a primary disinfectant as it is unable to maintain a residual in the distribution system. A secondary disinfectant such as chlorine, chloramines or chlorine dioxide is usually used with ozone for a complete disinfection system.

Ozone is not a halogen and therefore does not form any halogenated disinfection by-products (DBPs) during its reaction with natural organic matter in water. However, in the presence of bromides, the major ozone by-product of concern is bromate (BrO_3^-). The Guidelines for Canadian Drinking Water Quality established an interim maximum acceptable concentration (IMAC) level of 10μg/L for bromate. USEPA (1999) reported that bromate ion formation is an important consideration for waters containing more than 0.10 mg/L bromide ion. Ozone can also form other DBPs by reacting with aldehydes and ketones.

The principle advantages of using ozonation systems in drinking water treatment are as follows:

- More effective as a biocidal agent than chlorine, chloramines, and chlorine dioxide for inactivation of viruses, and protozoan species like *Cryptosporidium* and *Giardia*
- Highly efficient, as it requires less concentration and contact time
- Can control colour, taste and odour in drinking water
- Can oxidize iron, manganese, and sulfides
- Does not form halogenated disinfection by-products (THMs and HAA$_5$s)

The principle disadvantages of ozonation systems in drinking water are as follows:

- Harmful by-products like bromates, aldehydes, and ketones can be formed if the raw water has high concentrations of bromides and organic compounds
- Capital as well operational and maintenance costs are high for ozonation equipment
- Provides no residual protection and hence secondary disinfection is necessary
- Requires high level of maintenance and operator skill
- Requires off-gas destruction or quenching
- Tends to promote re-growth due to generation of BDOC/AOC unless BAF is used

It should be noted that because of the wide variation in system size, quality of raw water, and dosage of disinfectants applied, some of these advantages and disadvantages may not be applicable for certain water systems (USEPA 1999).

3.1.4   Ultraviolet Light

Ultraviolet light (UV) disinfection of water is a unique method of treatment, as it does not use chemicals for the inactivation of pathogenic microorganisms. UV radiation inactivates organisms by photochemical reaction with nucleic acids and other vital cell components essential to cell function. The optimum wavelength for disinfection is between 245 and 285 nm. Low-pressure UV lamps emit a narrow range with 85 percent of the light at 253.7 nm. Medium-pressure, high intensity lamps emit UV radiation over a wide range, primarily between 200 and 700 nm.

UV radiation is considered to be effective for inactivating bacterial and protozoan pathogens like *Giardia* and *Cryptosporidium*. Relatively higher doses of UV radiation are necessary for virus inactivation compared to other pathogens. Since UV disinfection does not provide any residual in water after treatment, it is usually followed by a secondary disinfectant to provide the residual protection. UV disinfection is a physical process and hence water quality parameters like temperature, pH, and alkalinity do not have a significant impact on the disinfection effectiveness. However, disinfection efficiency of UV reactors can be reduced significantly by the accumulation of solids on the surface of UV lamps. Waters having high concentrations of iron, hardness, hydrogen sulfide, and organics are more susceptible to scaling. Solids or particles can also affect disinfection efficiency by harbouring pathogens and protecting them from UV radiation. It is generally believed that higher turbidities (typically greater than 5 NTU) and suspended solids levels of water can reduce disinfection efficiency.

Often, there is a need to assess or validate the ability of commercial UV reactors to meet desired treatment goals. Such a process allows comparison of competing UV technologies with conventional systems. It also provides a level of comfort that a given UV lamp configuration will provide adequate protection of public health. This is important for UV systems because unlike chlorine residuals, ultraviolet radiation is not distributed uniformly throughout a reactor. Generally, a bioassay procedure is used to estimate the delivered dose of a reactor. The test typically involves an indicator organism like bacteriophage (MS2 phage), which is subjected to varying UV doses in the laboratory using a collimated-beam apparatus under different conditions.

The principle advantages of using UV systems in drinking water treatment are as follows:
- No increase in the concentration of biodegradable or assimilable organic carbon (AOC), thereby limiting the re-growth potential within the distribution system
- No concerns with respect to interactions with pipe material

- No known formation of disinfection by products (e.g., THMs, HAAs, aldehydes, bromate, ketoacids)
- To achieve the same log inactivation of *Giardia* and *Cryptosporidium*, it is less costly than ozone and chlorine dioxide
- When used in conjunction with chloramines as the secondary disinfectant, there is almost no formation of chlorinated DBPs of concern

The principle disadvantages of using UV systems in drinking water treatment are as follows:

- Higher dose is required to inactivate viruses
- No residual protection and hence the application of secondary disinfectant is necessary
- Difficult to monitor equipment performance
- Difficult to measure germicidal dose

3.1.5   Chlorine Dioxide

Chlorine dioxide is a powerful disinfectant. It is effective for inactivation of bacteria, viruses, and protozoa, including *Cryptosporidium*. As a disinfectant it is more effective than chlorine, but not as effective as ozone. Chlorine dioxide is also used for taste and odour control, and iron and manganese oxidation.

Chlorine dioxide in general forms fewer halogenated by-products than chlorine. The predominant end-product is chlorite (ClO_2^-). This has a significant impact on disinfection since chlorite is a regulated drinking water contaminant in the United States with a maximum contaminant level of 1.0 mg/L (USEPA 2003a). Based on a 50 to 70 percent conversion of chlorine dioxide to chlorite, the maximum dose is limited to 1.4 to 2.0 mg/L unless the chlorite is removed through subsequent treatment processes (USEPA 2003a).

The principle advantages of using chlorine dioxide in drinking water treatment are as follows:

- Effective against a wide range of pathogens in drinking water
- Does not form halogenated by-products.

The principle disadvantages of using chlorine dioxide in drinking water treatment are as follows:

- By-product formation of chlorite and chlorate limits the dosage of chlorine dioxide
- Less stable than other chlorine species and hence difficult to maintain an effective residual in the distribution system for a long time
- Disinfection efficiency is reduced significantly at low temperatures
- Significantly higher *CT* requirements for effective disinfection of *Cryptosporidium*
- Must be generated on-site
- Chemical costs are high
- Can be explosive at high temperatures and pressures
- Decomposes on exposure to sunlight and UV radiation

- • Documented cases of unusual smells ("kerosene-like" and "cat-urine like") in new homes due to reactions between unknown chemicals used in the preparation of carpet materials and gaseous chlorine dioxide in tap water.

3.1.6 Other Alternative Disinfectants

Hydrogen Peroxide

The use of hydrogen peroxide is not acceptable as a primary or secondary disinfectant in water treatment. Very few studies have been conducted with hydrogen peroxide to determine its efficacy against pathogens. Further, many of these studies (Yoshpe-Purer and Eylan 1968; Toledo et al. 1973; Lund 1963) did not document the dosage of the hydrogen peroxide applied in the water during disinfection.

Bromine

Bromine is highly reactive with ammonia and other amines, which may seriously limit its effectiveness under conditions typically found in water treatment. The data on the effectiveness of bromine against bacteria are complicated by the reactivity and the lack of characterization of the residual species in disinfection studies (NAS 1980). Hence, the use of bromine is not acceptable as a disinfectant for drinking water treatment.

Iodine

The use of iodine as a disinfectant for drinking water has not been extensive mainly because it is not cost effective. More studies are necessary to determine the consequences for human health of the long-term consumption of iodine in drinking water with special regard for more susceptible subgroups of the population (NAS 1980). The use of iodine is thus not acceptable as a disinfectant for drinking water treatment.

Applicability of other modes of disinfection

Throughout the history of water disinfection, mankind has tried a number of different methods for disinfecting drinking water. Some of these are potassium permanganate, silver, ferrate ionizing radiation, high pH conditions etc. Many of these have little scientific basis due to the lack of data, particularly data on the bacterial and virucidal efficacy. In some of them, the practical dosage of disinfectants necessary for effective disinfection is not available. In others the laboratory techniques used for measuring the disinfection effectiveness are not reliable. All these factors make these methods unreliable for application in drinking water disinfection. Hence, the use of these methods for the purpose of disinfection of drinking water is not acceptable. Water systems in Manitoba, particularly small drinking water systems, should refrain from using any of these methods for the purpose of water disinfection.

3.1.7 Summary of Disinfection Techniques

With increasing challenges for removing or inactivating some of the most resistant pathogens like *Giardia* and *Cryptosporidium*, while minimizing disinfection by-products, use of

alternative disinfectants are gaining popularity. Alternative disinfectants provide a variety of options. However, each of these alternative disinfectants has their own advantages and disadvantages. The efficacy of all the disinfectants varies significantly depending upon the type of pathogens and conditions like pH, temperature and water quality. In general, a summary of the characteristics of the various disinfectants is shown in Table 3.1.1, and their effectiveness on different pathogens in Table 3.1.2.

Table 3.1.1: Summary of Disinfection Techniques

Consideration	Chlorine	Chloramines	Ozone	Chlorine Dioxide	UV
Equipment reliability	Good	Good	Good	Good	Medium
Relative complexity of technology	Less	Less	More	Medium	Medium
Safety concerns	Low to High*	Medium	Medium	High	Low
Bactericidal	Good	Good	Good	Good	Good
Virucidal	Good	Medium	Good	Good	Medium
Efficacy against protozoa	Medium	Poor	Good	Medium	Good
By-products of possible health concern	High	Medium	Medium	Medium	None
Persistent residual	High	High	None	Medium	None
pH dependency	High	Medium	Low	Low	None
Process control	Well developed	Well developed	Developing	Developing	Developing
Intensiveness of operations and maintenance	Low	Moderate	High	Moderate	Moderate

*Safety concern is high for gaseous chlorine but it is low for hypochlorites.

Note: This is a general summary of the characteristics of alternative disinfectants and may not be applicable for all situations (Example: Safety concern is high for gaseous chlorine but low for liquid chlorine/hypochlorites).
Source: AWWA (1999) amended by Earth Tech (Canada) Inc.

Table 3.1.2: Effectiveness of Disinfectants on Different Pathogens

Disinfectant	Microorganism Reduction Ability			
	E. Coli	*Giardia*	*Cryptosporidium*	**Viruses**
Chlorine	Very effective	Moderately effective	Not effective	Very effective
Ozone	Very effective	Very effective	Very effective	Very effective
Chloramines	Very effective	Moderately effective	Not effective	Moderately effective
Chlorine dioxide	Very effective	Moderately effective	Moderately effective	Very effective
Ultraviolet radiation	Very effective	Very effective	Very effective	Moderately effective

Note: The reduction levels in the table are for normal dose and contact time conditions and they are only for general comparison purposes. The effectiveness of different disinfectants depends on the dose, contact time and water characteristics.

3.2   MULTIPLE DISINFECTANTS

As evident from the previous section, each of the alternative disinfectants has their own advantages and disadvantages. Often the multiple objectives of pathogen inactivation and providing residual protection in the distribution system are not achievable using a single disinfectant. In order to meet multiple objectives, the practice of using more than one disinfectant is not uncommon in water treatment. This practice where two (or more) disinfectants are added sequentially is sometimes referred to as "interactive disinfection". There may also be synergistic benefits where the net effect is better than the additive effect of the disinfectants in series.

The difference in purposes of primary disinfection and secondary disinfection in water supply allows each to be optimized independently. Primary disinfection is essential for the inactivation of microorganisms to meet the bacteriological reduction requirements while secondary disinfection is for meeting requirements to maintain the microbiological quality within the distribution system.

3.2.1   Primary Disinfectants

An effective primary disinfectant inactivates target microorganisms. Table 3.2.1 lists the potential primary disinfectants for four groups of target organisms with or without filtration.

Table 3.2.1: Potential Primary Disinfectants

Target Organism	Potential Primary Disinfectants
Coliform Bacteria	Chlorine Chloramines Chlorine dioxide Ozone UV
Giardia cysts	Chlorine Chlorine dioxide Ozone UV
Viruses	Chlorine Chlorine dioxide Ozone
Cryptosporidium oocysts	Chlorine dioxide Ozone UV

Source: USEPA 1999-Amended by Earth Tech (Canada) Inc.

3.2.2 Secondary Disinfectants

The choice of a secondary disinfectant is limited to those disinfectants that remain stable in the distribution system. In order of decreasing stability, the secondary disinfectants are chloramines, chlorine, and chlorine dioxide. Other disinfectants including ozone, UV, and in some cases chlorine dioxide, while producing effective microbial inactivation, do not produce a long-lasting residual.

3.2.3 Disinfectant Combinations

Various combinations of primary and secondary disinfectants can be used for disinfection. The viable combinations can be determined for the various treatment trains, since different treatment trains produce water with characteristics such as pH that can affect the disinfectants. Table 3.2.2 lists the combinations of disinfectants and their typical applications in water treatment.

**Table 3.2.2: Primary/Secondary Disinfectant Combinations
and Typical Applications in Water Treatment**

Primary / Secondary	Typical Application	Comment
Chlorine/Chlorine	Surface water and ground water disinfection.	Most commonly used disinfection scheme. High THMFP. Does not protect against *Cryptosporidium*.
Chlorine/Chloramines	Surface water and ground water disinfection.	Chlorine to provide disinfection and monochloramine to limit DBP formation. Moderate THMFP. Does not protect against *Cryptosporidium*.
Chlorine dioxide/ Chlorine dioxide	Surface water disinfection	High DBPFP. Primary and secondary usage requires a limit on chlorine dioxide dose to reduce residual chlorate/chlorite. Provides protection against *Cryptosporidium*.
Chlorine dioxide/ Chloramines	Surface water disinfection	High DBPFP. Primary chlorine dioxide dose limited to residual chlorate/chlorite. Provides protection against *Cryptosporidium*.
Ozone/Chlorine	Surface water disinfection	Highly effective against all pathogens including *Cryptosporidium*. Moderate THMFP. Moderate DBP formation. Can be applied only in waters having low bromide.
Ozone/Chloramines	Surface water disinfection	Highly effective disinfection against all pathogens including *Cryptosporidium*. Low THMFP. Moderate DBP formation. Can be applied only in waters having low bromide.
UV/Chlorine	Surface water and groundwater disinfection	Applicable only in low turbidity and high transmissivity waters. Highly effective against all pathogens including *Cryptosporidium*. High THMFP.
UV/Chloramines	Surface water and groundwater disinfection	Applicable only in low turbidity and high transmissivity waters. Highly effective against all pathogens including *Cryptosporidium*. Moderate THMFP.

Source: USEPA 1999-Amended by Earth Tech Canada Inc.

Notes: DBPFP = Disinfection by-products formation potential
THMFP = Trihalomethane formation potential
Low Bromide = Bromide concentration less than 1 mg/L
Low Turbidity = Turbidity less than 1 NTU

3.2.4   DBP Formation for Various Disinfectant Combinations

The types and amounts of DBPs formed by any disinfectant combination depend on the water quality, primary disinfection, secondary disinfection and preoxidants (if any) used. A specific combination that is appropriate for any one water quality may in fact cause an increase in DBPs when applied to another water quality.

No disinfectant combination has been found that is applicable to all situations. As a preoxidation step, chlorination of raw water with high NOM combined with chlorine as a secondary disinfectant produces the highest levels of XDBPs. Use of an alternative preoxidant that does not produce XDBPs and moving the chlorination point downstream of NOM removal processes will reduce the overall formation of XDBPs.

The choice of ozone is based on the bromide levels and the cost of providing biologically active filtration if higher AOC levels are a concern. In low pH, high bromide situations, brominated organic by-products are produced. In high pH and high bromide situations, bromate formation is favoured. The addition of chlorine dioxide will produce chlorite and chlorate and may form some oxygenated DBPs (e.g. maleic acids). Table 3.2.3 summarizes the potential DBPs formed by various combinations of disinfectants (USEPA 1999).

Table 3.2.3: DBPs Associated with Various Combined Oxidation/Disinfection Processes*

Alternative			Potential DBPs	Remarks
Pre-oxidation	Primary Disinfection	Secondary Disinfection		
Chlorine	Chlorine	Chlorine	XDBPs	Maximum XDBP formation compared to all other strategies. Principal components are TTHMs and HAA$_5$s.
			Aldehydes	Formed at relatively low levels.
Chlorine	Chlorine	Chloramines	XDBPs Cyanogen chloride Cyanogen bromide	Formation of XDBPs (specifically TTHMs and HAA$_5$s) significantly reduced compared to chlorine/chlorine/chlorine for short contact time
			Aldehydes	Formed at relatively low levels.
Chlorine dioxide	Chlorine dioxide	Chlorine	XDBPs	Formation of XDBPs may be decreased by delaying the point of chlorine addition.
			Aldehydes, carboxylic acids, maleic acids	Formed at relatively low levels.
			Chlorate Chlorite	Chlorite is a major breakdown product of chlorine dioxide.
Chlorine dioxide	Chlorine dioxide	Chloramines	XDBPs	Formation of XDBPs (especially TTHMs and HAA$_5$s) minimized by avoiding use of free chlorine.
			Aldehydes, carboxylic acids, maleic acid	Formed at relatively low levels.
			Chlorate Chlorite	Chlorite is a major breakdown product of chlorine dioxide.
Ozone	Ozone	Chlorine	XDBPs	Formation of certain XDBPs may increase or decrease compared to chlorine/chlorine/chlorine. Brominated by-products may be of concern when bromides are present in the raw water.
			Bromate, Aldehydes, carboxylic acids	Although formed at relatively high levels, significant amounts of this can be removed through biological filtration.
Ozone	Ozone	Chloramines	XDBPs Cyanogen chloride Cyanogen bromide	Formation of XDBPs (especially TTHMs) minimized by avoiding use of free chlorine.
			Bromate, Aldehydes, carboxylic acids	Although formed at relatively high levels significant amounts of this BOM can be removed through biological filtration.

Alternative			Potential DBPs	Remarks
Pre-oxidation	Primary Disinfection	Secondary Disinfection		
Chlorine	UV	Chloramines	XDBPs Cyanogen chloride Cyanogen bromide	May form XDBP from pre-oxidation
			Aldehydes	Low levels

*Source: USEPA 1999-Amended by Earth Tech (Canada) Inc.

Note: XDBPs - Halogenated Disinfection By-products

3.2.5   Synergistic Inactivation of Pathogens due to Sequential Disinfection

There has been a great deal of interest in the potential of interactive disinfectants because a number of studies have shown that when disinfectants are added sequentially, the combined effect is more than the sum total of its parts i.e. a synergistic effect is evident.

Kouame and Haas (1991) demonstrated a synergistic effect on the inactivation of *E. coli* when free chlorine and monochloramine were both used as disinfectants. Finch et al. (1995) reported superior inactivation of *Cryptosporidium* when using free chlorine followed by monochloramine in deionized water at room temperature when compared to either disinfectant alone. A more complete investigation (Gyürék et al. 1997) of chemical treatment combinations reported that the synergistic effect may be hindered at lower temperatures. Rennecker et al. (2000 and 2001) and Dreidger et al. (1999) studied ozone followed by free chlorine or monochloramine sequential inactivation of *Cryptosporidium* and reported a synergistic effect in buffered deionized water. Finch et al. (2000) and Li et al. (2001) concluded that pre-treatment with ozone increased the first-order rate of inactivation during subsequent exposure to free and combined chlorine and thereby generated a measurable synergistic effect. Oppenheimer et al. (2000) conducted a number of sequential disinfection experiments in different natural waters. They found a synergistic effect was evident but inconsistent in the various natural waters tested. More recently, Biswas et al. (2003) concluded that the synergistic effect of ozone followed by free chlorine for *Cryptosporidium* inactivation observed earlier in buffered deionized water is significantly reduced in natural waters at higher pH such as 8.0.

Some of the combinations of disinfectants typically used in water treatment which have shown some evidence of synergistic effect in earlier studies are as follows:

- Ozone followed by free chlorine
- Ozone followed by monochloramine
- Ozone followed by chlorine dioxide
- Chlorine dioxide followed by free chlorine
- Free chlorine followed by monochloramine

For some of the above combinations it was found that a high pH and low temperature significantly reduced the synergistic effect. The improved disinfection efficiency due to interactive disinfection is variable, ranging from negative (antagonistic) effects (in two studies) to positive enhancement of disinfection efficiency (USEPA 1999). The practice of sequential disinfection of water using chemical disinfectants is encouraged. However, more studies are necessary to conclude the presence of synergistic inactivation of waterborne pathogens. Synergistic disinfection also should not be used to replace any traditional method of water treatment such as filtration. It should rather complement and provide additional protection on top of the regular multiple barriers typically provided by water systems against waterborne pathogens.

3.3 DISINFECTION FOR SMALL DRINKING WATER SYSTEMS

In this manual, "small" drinking water systems are referred to as ones serving less than 1000 people. In general, small drinking water systems face special challenges for water treatment. The two major challenges for small drinking water systems are affordability and technical complexity. Affordability is a critical issue, as the costs for each customer in a smaller system tend to be higher and often they cannot afford to install a prescribed technology. Small drinking water systems also do not have access to well-trained operators (USEPA 1997).

Chlorination is the most widely used disinfectant for small water systems. However, the use of gaseous chlorine is not preferred. This is because the use of gaseous chlorine places greater demand on the need for isolated plant space, trained and attentive operating staff, protection from hazards, and raises the liability issues which can boost insurance costs (USEPA 1997). Hypochlorite in either liquid or solid form is the preferable disinfectant for small drinking water systems.

Chloramines are not very common in small drinking water systems. The main issue with chloramination in small drinking water systems is the requirement for a careful operation and monitoring program. Improper operation of a chloramination facility can cause nitrification, which may be difficult for small drinking water systems to handle due to the added costs and monitoring.

The application of ozone for smaller water systems is rare mainly due to cost and complexity of operation. However, a number of suppliers offer a number of ozone systems even for smaller applications. The effective operation of ozone systems at low temperatures is particularly important as the disinfection requirements for ozone are very high under these conditions.

For UV systems, the simplicity of installation, ease of operation and maintenance, and low costs relative to chemical disinfection make it a very attractive small system disinfection technology (USEPA 1997). However, the water may require some form of pre-treatment (like

filtration) before UV application to increase transmissivity. Some form of validation of the UV equipment is required to ensure effective disinfection in small drinking water systems.

Chlorine dioxide can be very effective against all kinds of pathogens. However, it is limited in small drinking water systems due to high cost, complexity, safety concerns, and intensiveness of operation and maintenance.

Among all the disinfectants, chlorination (as hypochlorites) is the most simple, affordable and popular in small drinking water systems. It provides the necessary bacterial and viral protection in the water. If disinfection by-product precursors and protozoan parasites in the raw water do not pose a major problem (like in groundwater or raw waters with low organic carbon content), chlorination can be effectively used as a disinfectant to meet both microbial standards and disinfection by-product limits.

Compliance monitoring is one of the key tools for ensuring that smaller water systems are achieving effective disinfection. The compliance monitoring requirements vary by the size and type of the system, the treatment employed, and the disinfectant used (USEPA 1997).

3.4   ALTERNATIVE DISINFECTANT SELECTION

3.4.1   Determining the Necessity of Alternative Disinfection

Due to the growing recognition for the need to protect the public from illness caused by contaminated drinking water, drinking water standards are changing throughout the world. Often the conventional disinfection techniques were not found to be sufficient given the water quality standards required for the finished water. The use of alternative disinfection is thus increasing in order to achieve the desired water quality.

Selection of an appropriate alternative disinfection technology should fulfil the following objectives (USEPA 1999):

- Provide drinking water free from pathogens like bacteria, viruses, and protozoan cysts or oocysts
- Prevent the formation of disinfection-by-products in the drinking water which can cause long-term health effects
- Prevent microbial growth and maintain high quality water in the distribution system.

Figure 3.4.1 shows the flowchart for determining the necessity of alternative disinfection. The flowchart emphasizes the fact that when the above objectives are not fulfilled in the existing utility even after process modifications such as the introduction of filtration, the use of alternative disinfectant is highly prudent from a public health perspective.

```
                    ┌──────────────────────────────────┐
          Yes       │  Meet current microbial standards and │      No
     ┌──────────────│   disinfection-by-product limits    │──────────────┐
     │              └──────────────────────────────────┘              │
     │                                                                 │
     ▼                                                                 ▼
┌──────────────┐                                        ┌──────────────────┐
│   Improve    │                                        │  Goals achieved with │
│ protection level? │                                   │ process modifications? │
└──────────────┘                                        └──────────────────┘
     │         ╲                                          ╱          │
  No │      Yes ╲                                    No  ╱        Yes │
     │           ╲                                      ╱            │
     ▼            ▼                                    ▼             ▼
  ╭────╮    ╭──────────────╮                              ╭────╮
  │ OK │    │   Evaluate    │                             │ OK │
  ╰────╯    │  alternative  │                             ╰────╯
            │  disinfectant │
            ╰──────────────╯
```
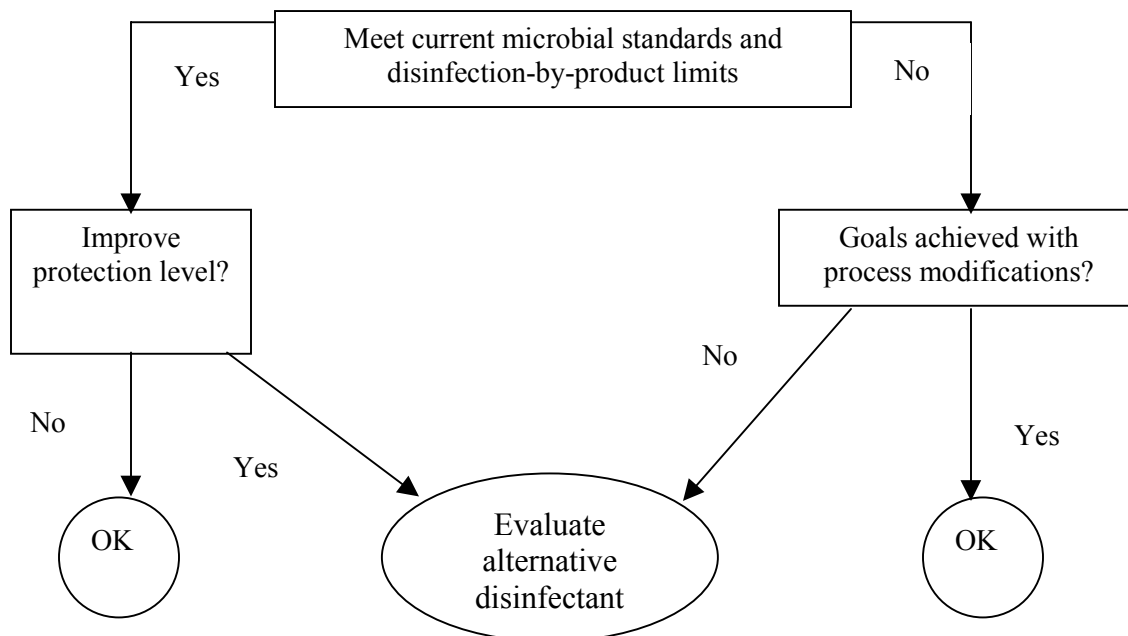
Figure 3.4.1: Flow diagram to determine the necessity of alternative disinfectants

3.4.2 Disinfectant Selection

When selecting a disinfectant, a water utility first needs to assess their treatment system and determine what level of additional protection they need in order to meet their treatment objectives. Most water systems will need to use a combination of disinfectants. In this manual selection guidelines for both primary and secondary disinfection are provided for different types of water systems:

- Water systems with or without filtration
- Water systems which use either surface water or groundwater as their source
- Small drinking water systems providing water to less than 1000 people.

Figures 3.4.2 to 3.4.4 show flow charts for the selection of disinfectants for various types of water systems. The decision making process was developed based on certain critical issues which strongly influence the disinfection and by-product requirements. Some of the factors that were used for the decision making process are as follows:

TOC concentration: A high *TOC* concentration is an indication of a high potential for DBP formation (USEPA 1999). Water having high *TOC* is very likely to form halogenated DBPs by the addition of certain chemical disinfectants such as chlorine. However, water systems may still choose to use chlorine provided they remove the organics (*TOC*) or DBPs at some later stage of treatment. Water systems may also choose to apply a small dose (*CT*) of these disinfectants just sufficient enough to provide the necessary microbial inactivation, but prevent formation of harmful level of DBPs in the finished water. A possible example of this

kind of scenario is chlorination for a short contact time for virus inactivation followed by the addition of ammonia to form chloramines just prior to the storage reservoir in order to provide the necessary residual protection.

Assimilable Organic Carbon (AOC) Concentration: AOC is produced when a strong oxidant such as ozone is used as a primary disinfectant in the presence of high TOC water (USEPA 1999). Hence, AOC should only be measured when ozone is used as a primary disinfectant in high TOC water. In such cases, the use of biological or GAC treatment is recommended to stabilize the finished water and prevent re-growth in the distribution system.

Turbidity: In water, turbidity measurement is a relatively crude means of detecting a wide variety of particles from a wide assortment of sources; but it does not provide any information about the nature of particles (AWWA 1999). In general high turbidity waters have low UV absorbance, which significantly reduces the efficiency of UV systems for water disinfection. High turbidity waters may also contain high suspended solids, which can protect pathogens from coming in contact with chemical disinfectants. High turbidity waters can also reduce the efficiency of disinfection by increasing the disinfectant demand and decay rate (AWWA 1999). This can significantly reduce the overall *CT* applied in the water. Most of the *CT* tables developed earlier do not take into consideration the influence of turbidity. Hence the influence of turbidity on pathogen inactivation kinetics as well as the chemical disinfectant demand and decay characteristics for many disinfectants is largely unknown. Thus it is recommended that unfiltered water systems using chemical disinfectants in high turbidity water carry out some bench or pilot scale studies in order to develop their own models for pathogen inactivation kinetics and disinfectant demand and decay characteristics. While carrying out these studies changes in water quality characteristics due to seasonal variations should be taken into consideration. The other option is to use an additional treatment unit for reducing the turbidity to less than 1 NTU. In such cases, the influence of turbidity is minimal.

Bromide Ion Concentration: The principle reason for including the bromide ion concentration in the flow chart is to determine the applicability of ozone in the water system. Ozone reacts with bromide ions to form bromates, which are considered to have potential long-term adverse health effects. Hence, the use of ozone is not recommended for water systems having high concentrations of bromide ions.

Disinfection Byproduct Formation Potential (DBPFP): DBPFP gives an indication of the potential of forming DBPs. This is important because secondary disinfectants are responsible for protecting the water through a complex terrain in the distribution system until it reaches the taps of consumers. DBPFP can be determined with the help of simulated distribution system (SDS) tests. SDS tests consider a number of factors including the effects of increased disinfectant demand exerted by the internal pipe walls in the distribution system (Brereton and Mavinic, 2002). SDS tests are useful for larger water systems where the distribution system is large and complex.

Figure 3.4.2: Flow diagram to select a primary disinfectant for large drinking water systems using surface water without filtration
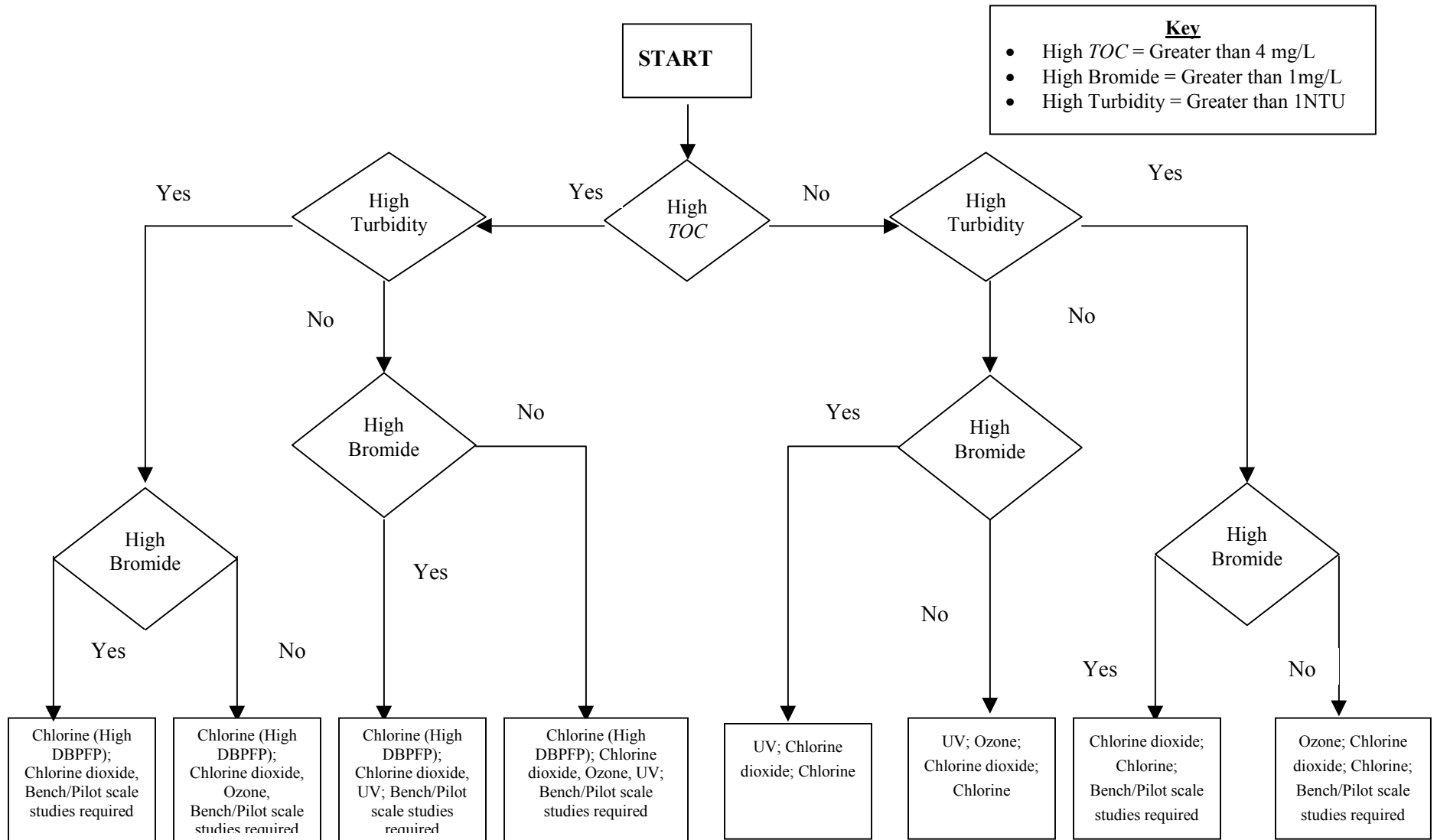
Source: USEPA 1999-Amended by Earth Tech

Figure 3.4.3: Flow diagram to select a primary disinfectant for large drinking water systems using surface water with filtration

Key
- High *TOC* = Greater than 4 mg/L
- High Bromide = Greater than 1 mg/L
- DBPFP = DBP formation potential
- Assumption: Turbidity less than 1 NTU

START

Yes   High Bromide   Yes   High *TOC*   No   High Bromide   Yes

No   No

UV; Chlorine dioxide; High DBPFP; Bench/Pilot scale studies required

UV; Ozone; Chlorine dioxide; High DBPFP; Bench/Pilot scale studies required

UV; Ozone; Chlorine dioxide; Chlorine

UV; Chlorine dioxide; Chlorine

Source: USEPA 1999-Amended by Earth Tech (Canada) Inc.

Figure 3.4.4: Flow diagram to select a secondary disinfectant for large drinking water systems using surface water
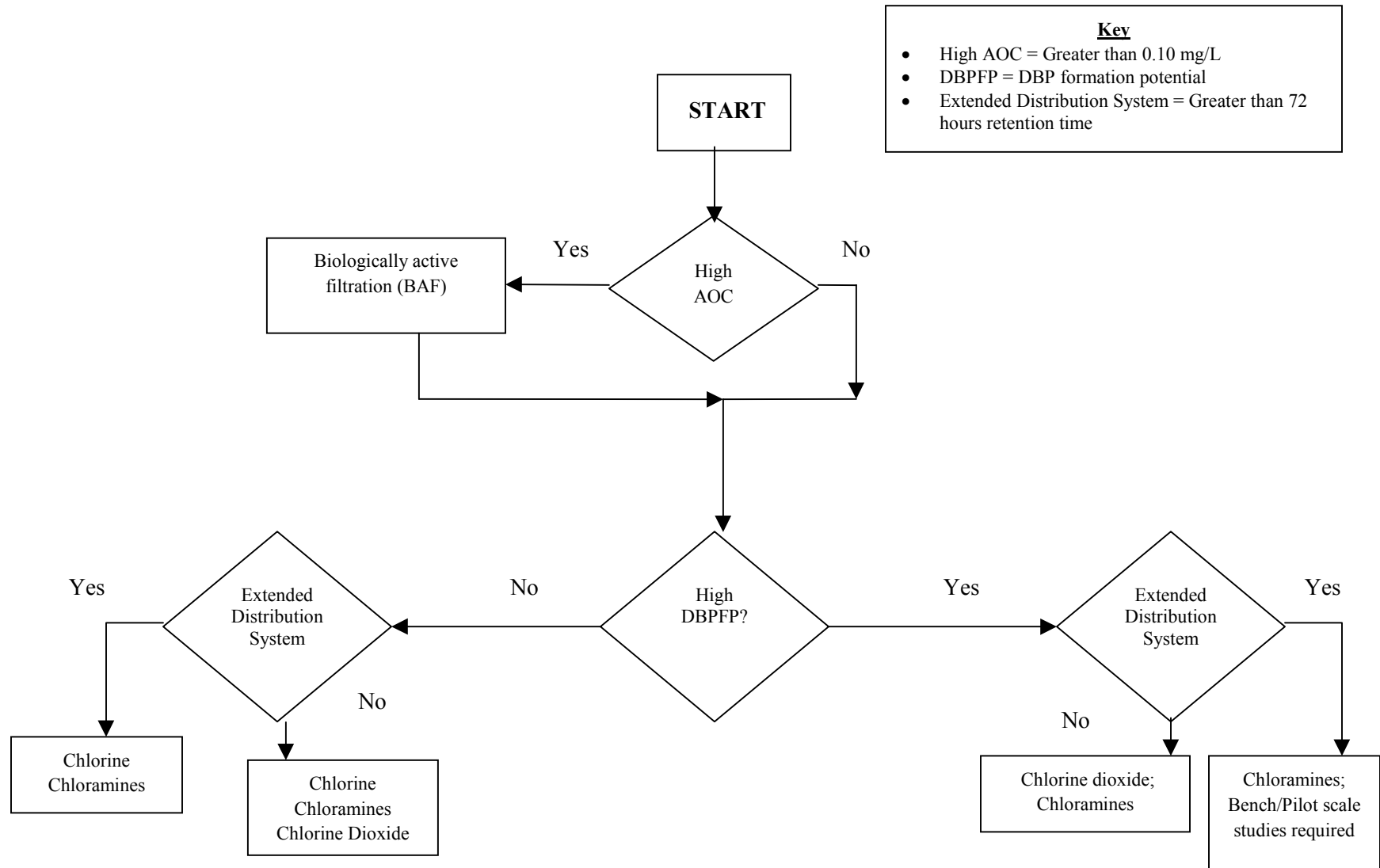
Source: USEPA 1999-Amended by Earth Tech (Canada) Inc.

Extended Distribution System: For an extended and complex distribution system, the role of the secondary disinfectant is highly important. The ability of the disinfectant to maintain the residual protection throughout the distribution system needs to be proven. Often booster re-chlorination stations may be required to maintain the required disinfectant residual. The choice and dosage of the disinfectants also becomes important. Hence, extended distribution systems influence the choice of secondary disinfection in a significant way.

It is recommended that these flow charts be used as a general guide in the selection of alternative disinfectants for water treatment and not as the only tool for effective selection. This is because selection of an alternative disinfectant depends on a number of factors. Since each utility has a unique combination of raw water characteristics, climatic conditions, size and complexity of operation; final selection of a disinfectant should be made by evaluating the site-specific conditions unique to each utility. This may require a thorough engineering evaluation including bench or pilot-scale testing.

3.4.3   Selection of Disinfectants for Groundwater

Groundwater forms an important source of water supply in Manitoba. In general, groundwater requires less treatment compared to surface water because of the ability of groundwater to protect itself from external sources. It is the preferred source of water supply where minimal treatment is a high priority like small drinking water systems and private wells. Groundwater however can be subjected to contamination. A common conclusion of all groundwater contamination studies is that prevention is better than treatment in assuring the quality of groundwater supply sources (AWWA 1999). Some of the most important influencing factors in groundwater contamination in Manitoba are as follows:

- Livestock operations
- Municipal waste disposal grounds
- On-site sewage systems (fields, tanks etc.)
- Underground fuel storage tanks

Some of the pathways by which pathogens may enter groundwater include leaching through the soil to the water table with infiltration via poorly constructed or maintained wells and unplugged boreholes, or via direct transport from subsurface wastewater disposal sites to wells. The primary source of pathogens contaminating groundwater is faecal waste and waste systems like manure, biosolids and septic systems (CCME 2002). All of these factors can contribute to microbial health problems. The most common microbial health problem associated with groundwater is the occurrence of coliform bacteria. Most bacterial problems can be eliminated by proper well construction practices, locating wells up-gradient from potential sources of contamination and proper well maintenance (NHRI 1995). Bacteria are not the only organisms that can contaminate groundwater. Other pathogens that pose a threat include viruses and protozoa. Groundwater supplies that are particularly at risk from

pathogens are those wells which are (1) shallow, (2) improperly constructed and maintained, and (3) wells under the direct influence of surface water. In spite of the advantages of using groundwater as a source, some form of disinfection is recommended for all water systems (small and large) in order to prevent bacterial re-growth in the distribution system. Figure 3.4.5 shows the flow chart for selecting disinfectants for groundwater systems. Some of the factors, which influence the selection process, are described in the following paragraphs.

Groundwater under the direct influence of surface water (GUDI): Water systems whose ground water source is under the direct influence of surface water are vulnerable to contamination by pathogens. For disinfection purposes, GUDI may be treated as surface water as currently we do not have a good understanding of pathogen transport in groundwater. The addition of filtration and a combination of primary and secondary disinfection may be necessary.

In Manitoba, according to the Drinking Water Standards Regulation, a water system's source of water supply is deemed to be GUDI if the water supply is groundwater that has a significant occurrence of insects or other microorganisms, algae, organic debris or large diameter protozoa or pathogens such as *Giardia lamblia*. A significant and rapid shift in water characteristics such as turbidity, temperature, conductivity, or pH, which closely relates to climatological or surface water conditions, is also an indication of a GUDI. Springs, infiltration gallery and certain wells may be deemed GUDI depending upon locations, method of construction and conditions. Large drinking water systems may also consider doing hydrogeological assessments for determining GUDI.

The accurate determination of GUDI is very critical in the application of alternative disinfectants. Groundwater sources, which are wrongly determined as "non GUDI" may receive an insufficient level of disinfection, which can result in waterborne disease outbreaks. Public health protection may then be compromised significantly.

Residual Protection: It is recommended that under all circumstances, a minimum treatment of chlorine or chloramines be practiced for all groundwater systems. This is primarily for disinfectant residual protection in the distribution system. The water should receive sufficient dosage for continuous maintenance of residuals in the distribution system. Where water quality is a concern, primary disinfection is required.

Figure 3.4.5: Flow diagram to select disinfectants for groundwater systems
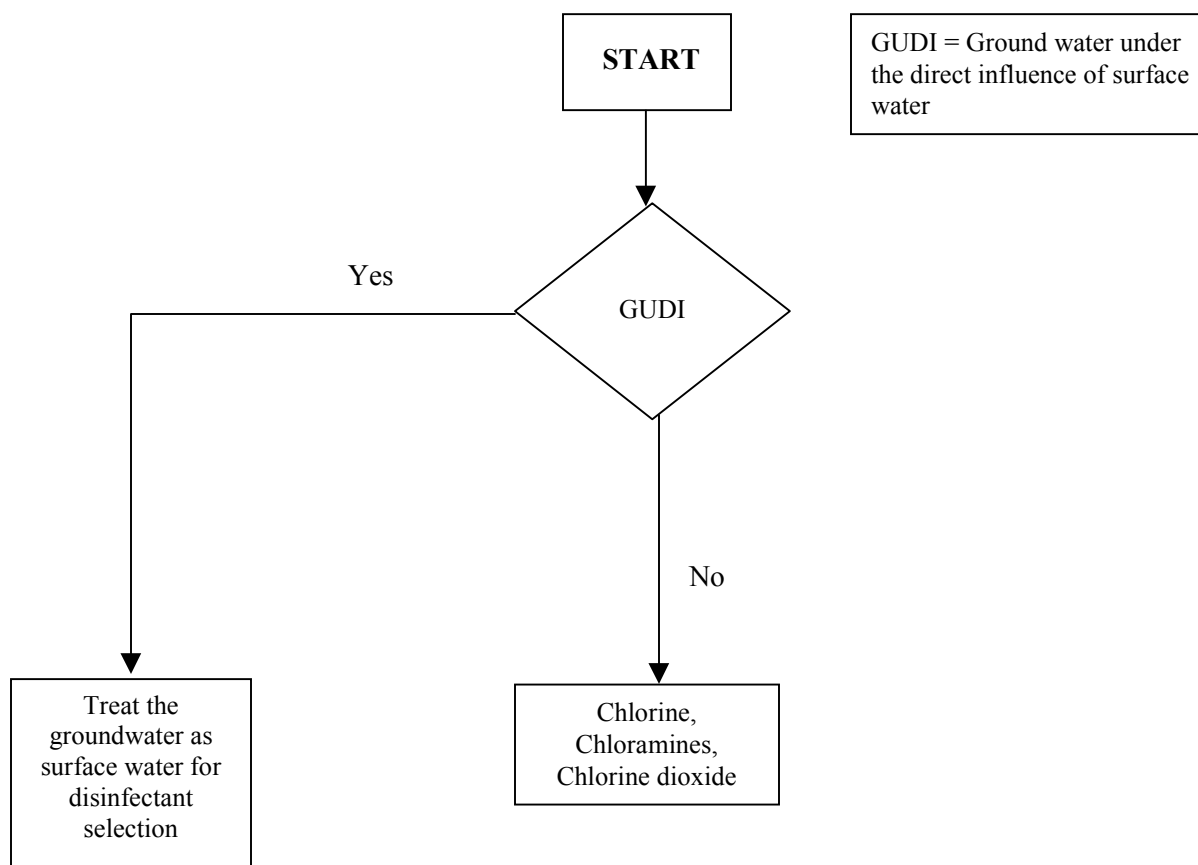
3.4.4   Selection of Disinfectants for Small Drinking Water Systems

For small drinking water systems, the recommendations for the application of alternative disinfectants for medium or large drinking water systems may not be practical. This is because the cost involved in carrying out all the recommendations may not afford a reasonable rate of return on investment towards guaranteeing safe drinking water (NHMRC 1996). Hence, this section provides some recommendations, which can be implemented by smaller communities without compromising public health protection.

Figure 3.4.6 shows the steps for disinfectant selection to be followed by small drinking water systems. The steps are discussed below.

Testing of source waters: For small drinking water systems, successful management of water quality is a key step in protecting the water against potential contamination. This requires an understanding of the water supply system. Determining the quality of source water for all aspects (physical, chemical, and microbiological characteristics) and considering seasonal

variations are important steps towards that goal. The water quality parameters identify the level of contaminants currently present in the source water, which helps to determine the level of treatment required for the water.

Identify potential sources of contamination: Some water sources may be vulnerable to sudden contamination due to natural, human and animal activities. Identifying potential sources of water contamination is an important step in determining the system vulnerability and inspection requirements. Some of the natural, human and animal activities often responsible for contamination of source waters are (NHMRC 1996):

- Dumping of animal carcasses
- Animal excrement
- Use of agricultural pesticides and fertilizers
- Soil erosion
- Mining industry wastes
- Leakage from underground fuel storage tanks, waste disposal sites and septic tanks
- Leaching of agricultural chemicals and fertilizers
- Spills and industrial effluents

Successful identification of the potential sources of contamination can help in designing a system management scheme that can reduce the risk of water contamination significantly. Steps should be taken to protect the water sources as much as possible. Some of these steps include (NHMRC 1996):

- Regular inspections to check for any direct or potential sources of contamination of the water supply
- Monitoring microbiological indicator organisms (Total Coliforms and *E. Coli*)
- Adopt a standard protocol for inspection and monitoring requirements
- System management of every aspect of the water system, right from source to tap
- Land use restrictions

Figure 3.4.6: Flow diagram to select disinfectants for small drinking water systems
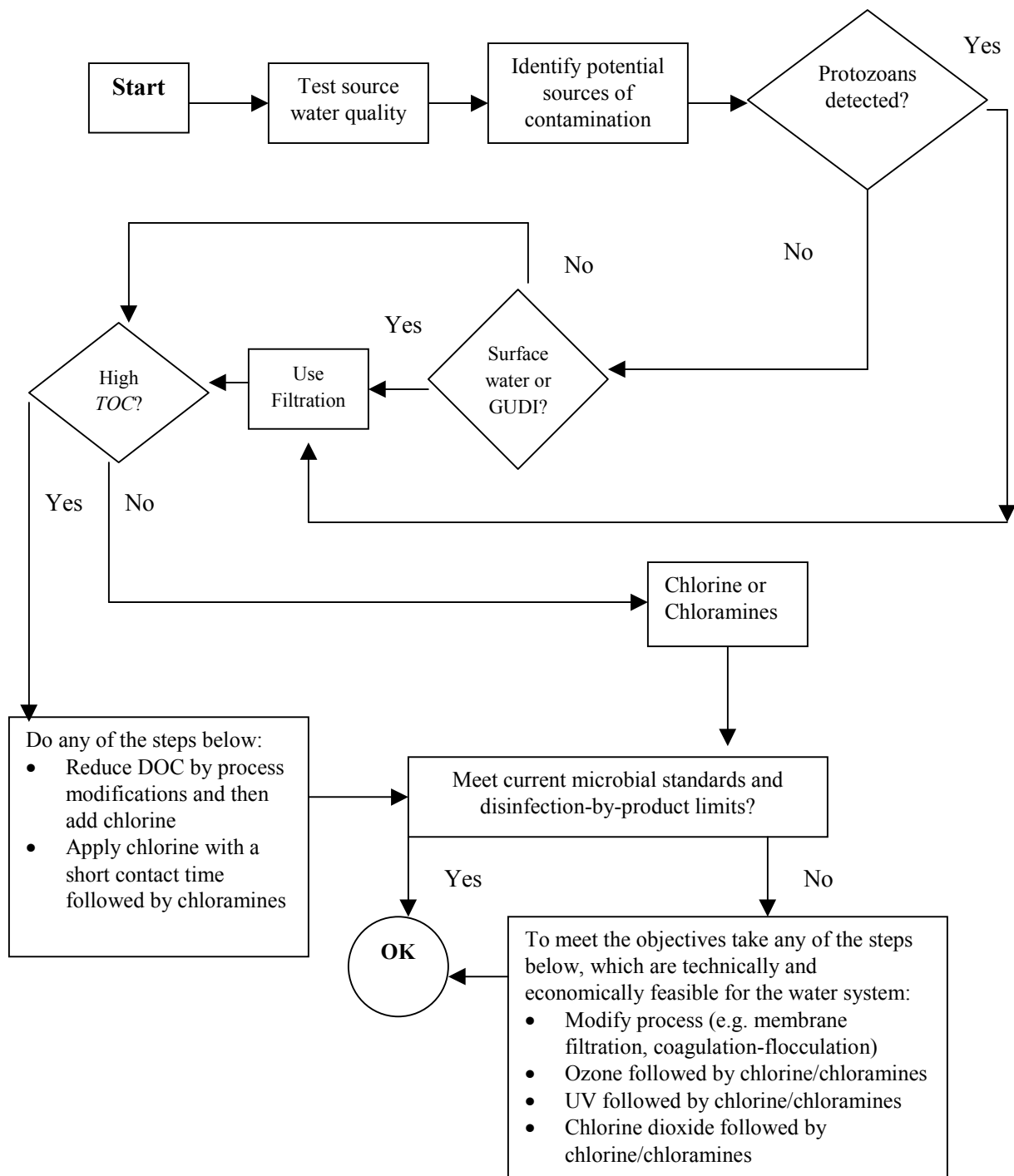
Inspection is one of the most critical aspects for small drinking water systems for protection against outbreaks due to waterborne diseases. The frequency of inspection of water sources depends on the characteristics of each site, raw water source, storage system, and the subsequent treatment system, that is provided (NHMRC 1996).

Monitoring is an effective method for identifying contamination for a narrow range of key characteristics. This often supplements a sanitary survey, which is a comprehensive and lengthy process of analyzing the vulnerability of a water supply treatment and distribution system. As a minimum, small communities should monitor the following four characteristics:

- Total Coliforms and *E. Coli*
- Disinfectant residual levels
- pH
- Turbidity

Monitoring is especially important for small drinking water systems where laboratory support is lacking or where transportation problems would render conventional sampling and analysis difficult or impossible (NHMRC 1996).

System management is also an effective method of protecting small drinking water supplies. System management essentially includes management of every aspect of the water system, right from source to tap. Some of the measures for preventing potential contamination of water in small drinking water systems include (NHMRC 1996):

- Effective management of point sources of pollution such as human and industrial waste discharges
- Best agricultural practices for the reduction of the impact of non-point sources of pollution such as agricultural and livestock operations
- Control of the clearing of vegetation in order to prevent soil erosion
- Addition of filtration before disinfection in order to reduce high loadings of suspended solids
- Maintenance of all equipment in good condition
- Monitoring the quality of water in storage systems
- Selection of an effective disinfection process
- Maintenance of disinfectant residual in the finished water before it reaches the consumers.

Protozoans detection: The detection of a significant number of protozoans like *Giardia* and *Cryptosporidium* in the raw water is an alarm signal for water systems. This is because these microorganisms are much more resistant to chlorine disinfection than viruses and bacteria. Presence of significant levels of protozoans poses a risk for waterborne disease outbreaks. Removal or inactivation of significant levels of protozoans in the raw water requires more advanced level of treatment. Application of filtration then becomes mandatory. Effective filtration can achieve approximately 2-log (99%) inactivation of pathogenic protozoa. Alternative disinfectants like ozone, UV, and chlorine dioxide can also be effective for protozoan inactivation.

Surface water or GUDI: Even if significant levels of protozoans are not detected, surface water or groundwater under the direct influence of surface water (*GUDI*), are particularly

vulnerable to protozoan contamination. As a precautionary measure, the use of filtration is then recommended. The use of alternative disinfectants can also be used if it is found to be technically and economically feasible.

High TOC or *DBP precursors*: A high *TOC* (> 4mg/L) concentration is an indication of a high potential for DBP formation (USEPA 1999). Water having high *TOC* is very likely to form halogenated DBPs by the addition of chlorine. Hence, for the application of chlorine it is necessary to reduce the level of *TOC* or disinfection by-product precursors concentration.

Chlorine: The microbiological quality of water is by far the most important factor in determining the safety of water supplies from a health perspective (NHMRC 1996). Hence adequate disinfection is an essential requirement for protecting small drinking water systems. Economic constraints on smaller systems often limit the use of alternative disinfectants, which can be expensive and complex in terms of operation. However, disinfection such as chlorination is an absolute necessity for small drinking water systems, in order to provide the residual protection and prevent re-growth of microorganisms in the finished water. An adequate dosage of chlorine can also provide some protection against re-contamination of finished water from backflow, pipeline breaks or other causes. Some protozoan pathogens such as *Cryptosporidium* are resistant to chlorine. Nevertheless, chlorination is still regarded as the most appropriate key defence against microbiological contamination for small drinking water systems (NHMRC 1996).

Meet current microbial standards and disinfection-by-product limits: It is possible that even after the use of chlorination, microbial standards may not be met due to the presence of high levels of protozoan parasites such as *Giardia* and *Cryptosporidium* in the raw water, against which chlorine is less effective. It is also possible that the disinfection by-product limits or standards may not be met. In such scenarios, it is up to the small drinking water system to develop a feasible solution for protection of their water system. For the reduction of DBP precursors/ *TOC*, the solution may be in the form of process modifications such as pre-treatment or adsorption. However, process modification is generally not a cost effective approach to baseline *TOC* removal. For the reduction of protozoan pathogens the solution may be in the application of alternative disinfectants like ozone, UV, chlorine dioxide, chloramines or multiple disinfectants. Some of the possible combinations of disinfectants, which can be used by small drinking water systems, are as follows:

- Ozone followed by chlorine/chloramines
- UV followed by chlorine/chloramines
- Chlorine dioxide followed by chlorine/chloramines
- Chlorination for a short time followed by chloramination

It is important to evaluate both the technical feasibility and the economic feasibility of these options. Validation of the alternative disinfectants for small drinking water systems can be

demonstrated by using NSF or similarly certified water treatment equipment. Since on-site validation may not be feasible for small drinking water systems, applying a conservative dosage of disinfectants or using a higher safety factor is prudent from a public health perspective. It is very important for small drinking water systems to realize that alternative disinfectants should not be used to replace chlorination without serious consideration of public health implications. Chlorination will act as the last line of defence if the alternative disinfection fails.

If microbiological contamination of water cannot be prevented some of the options for smaller communities are:

- Seek an alternative source of raw water
- Upgrade substantially the barriers to contamination in order to achieve guideline values

If the microbiological safety of the water is in question the province may issue a boil water advisory until the problems are solved.

When a very small water supply serves an isolated establishment, such as a motel or an individual household, implementation of the above recommendations sometimes become unrealistic (NHMRC 1996). Nevertheless, a minimum treatment of chlorination is recommended. For such establishments the selection of the best quality source water and protecting its quality by the use of multiple barriers and maintenance programs are recommended. Microbiological monitoring should be carried out. The establishments should also consider having the water tested for key water quality characteristics identified as being a local concern. Information on the quality of surface and groundwater may be available from local or provincial governments who monitor particular source waters as part of local or provincial water-monitoring programs.

SECTION 4.0
APPROVALS PROCESS

4.1   INTRODUCTION

In addition to the distinction between small and large drinking water systems used in this document, the Office of Drinking Water (ODW) of the Province of Manitoba categorizes water systems as: Public Water System, Semi-Public Water System, or Private Water System.

Public Water System means a water system that has 15 or more water service connections.

Private Water System means a water system that supplies water only to one private residence.

Semi-Public Water System means a water system that is not a public water system or a private water system.

The ODW can also designate a semi-public system as either a public or private system based on public health risk considerations. This chapter of the Guidance Manual has been prepared to outline the procedures to be undertaken by proponents to obtain approval for the utilization of alternative disinfectants.

4.2   APPROVALS PROCESS

All public and some semi-public water systems (once new regulations are in force) are required to obtain written approval for the construction of upgrading of a drinking water treatment and/or disinfection system. The following section outlines the step-by-step process for obtaining such an approval:

STEP 1

All proponents should submit a "Letter of Intent" stating clearly what treatment and/or disinfection scheme is proposed for their utility and justification for its usage. The proponent should also discuss in general the proposed source of water supply, water treatment process, residual management system, expected treated water quality, and any expected significant environmental impacts. The ODW staff will review the "Letter of Intent" and assess the justification of the treatment process for the utility. The ODW will advise the proponent about any additional requirements that will be required for the approval process.

STEP 2

After the province reviews the "Letter of Intent", the proponent should submit a pre-design report including details of testing protocols and any bench/pilot scale studies if applicable. The ODW will review and approve the pre-design report based on certain conditions. The proposed treatment and/or disinfection system is approved in principle for works whose detailed engineering design has not been finalized but for which the design has advanced to

the stage where all significant technical decisions having a potential to affect performance and/or environmental impact of the works have been already made. This step may not be required for small drinking water systems, depending on the scope of work proposed.

STEP 3

At this stage, the project proponent is required to submit an application for a construction permit along with final engineering design drawings, specifications, and design data (if not included in the pre-design report). Once the application is submitted, it is reviewed by the ODW for the completeness and adequacy of the detailed design documentation and other supporting information. The compliance of the proposal with the Department's acts, regulations, policies, objectives, and guidelines are evaluated in detail. In the process of this detailed review, the ODW may determine that additional information is necessary for proper assessment of the application. A request for such information is typically made in the form of a letter to the proponent, which may include a deadline for the response. In the process of the detailed review, if it is determined that the proposed disinfection system and any other proposed works would not be capable of consistent compliance with the Department's acts, regulations, policies, objectives or guidelines, or that the engineering design does not conform to the principles of sound engineering, the ODW will advise in writing that the proposed facilities as designed cannot be approved. If it is found that everything is in order, a permit will be issued for the works. Construction of the proposed works can begin as approved by the permit issued by the ODW.

STEP 4

Depending upon the terms and conditions of the permit, proponents may be required to carry out and submit validation testing and/or verification of the disinfection equipment under site-specific conditions. For small drinking water systems, validation can be demonstrated by using NSF, CSA or equivalent certified equipment for disinfection.

STEP 5

Once the approval conditions for construction have been met the proponent must apply for an operating licence if the disinfection system is part of a new water system or an amendment to their existing operating licence. The terms and conditions of the licence will include any requirements related to the performance, operation and maintenance of the disinfection system, monitoring and reporting, emergency planning, and contingencies to deal with accidental spills, contamination, or upsets.

For the benefit of the proponents, a general checklist of items to be considered by all water systems for the implementation of disinfectants is provided in Appendix B. Since the design of any water treatment process depends on site-specific conditions, the checklists should not be used as the sole guidelines for design. Rather, they should be used as basic guideline for implementing disinfection systems, and for streamlining the approval process.

Figure 4.1: **Steps of the Approval Process for the Installation and Operation of a New or Upgraded Disinfection System in a New or Existing Water System**

```
    Start  ──────────▶  Letter of   ─ ─ ─ ─ ─ ─ ▶   Reviewed
                         Intent                      by ODW
                            │
                            ▼
                 Submit pre-design report
                 including testing protocols, and
                 bench/pilot scale data          ─ ─ ─ ─ ▶   Approved
                 (Optional/Can be waived by                  by ODW
                 ODW)
                            │
                            ▼
                 Submit formal Construction
                 Permit application including   ─ ─ ─ ─ ▶   Approved
                 design details and drawings                by ODW
                            │
                            ▼
                     Construction
                            │
                            ▼
                 Perform Testing/Validation
                 (Optional/Can be waived by ODW)
                            │
                            ▼
                 Submit formal application for Operating   ─ ─ ▶   Approved
                 License or Amendment                              by ODW
                            │
                            ▼
                      Operation
```

SECTION 5.0
BEST PRACTICES MANUAL

5.1   INTRODUCTION

There are several guideline documents published earlier, which contain valuable information about alternative disinfectants in water treatment. Some of these are as follows:

1. Saskatchewan Environment. *A Guide to Waterworks Design*, 2002.

2. *Ten States Standards* or GLUMRB (Great Lakes-Upper Mississippi River Board of State and Provincial Public Health and Environmental Managers). *Recommended Standards for Water Works,* Health Education Services, Albany, NY, 2003 edition.

3. Ministry of Environment, Ontario. *Procedure for Disinfection of Drinking Water in Ontario*, 2003.

4. Alberta Environment Protection. *Standards and Guidelines for Municipal Waterworks, Wastewater, and Storm Drainage Systems*, 1997.

5. United States Environmental Protection Agency, *Alternative Disinfectants and Oxidants Guidance Manual*. 1999.

6. United States Environmental Protection Agency. *Long Term* 2 *Enhanced Surface Water Treatment Rule-Toolbox Guidance Manual*, 2003.

7. United States Environmental Protection Agency. *Draft Ultraviolet Disinfection Guidance Manual*, June 2003.

8. AWWA (American Water Works Association). *Guidance Manual for Compliance with the Filtration and Disinfection Requirements for Public Water Systems Using Surface Water Sources*, McGraw-Hill, New York, NY, 1991.

This chapter of the manual provides a detailed discussion on various alternative disinfectants that may be used in water treatment in Manitoba. It highlights a number of issues critical to water treatment and it also provides best practices for alternative disinfection.

5.2   GENERAL DESIGN, OPERATIONAL AND MONITORING PRACTICES OF DISINFECTION

In chemical disinfection, the concept of *CT* (i.e. product of disinfectant residual concentration and effective disinfectant contact time) is used to quantify the capability of a disinfection system to provide effective pathogen inactivation to the desired level. The use of this concept involves the determination of *CT* values required at the actual operating conditions (flow, temperature, pH and chlorine residual) and ensuring that the employed disinfection process achieves these values at all times (MOE 2003). The *CT* requirements for all disinfectants

discussed in this document are provided in tables and graphs later in the respective sections of this chapter. They are also summarized in Appendix-A.

The USEPA uses the following *CT* equation as the main criteria for design and performance analysis of disinfection systems:

$$log \ N/N_o = -kCT$$

where:

log N/N$_o$	=	Log reduction of microorganisms
CT	=	Product of disinfectant residual concentration and effective disinfectant contact time
k	=	Microorganisms reduction constant
N	=	Microorganisms concentration after inactivation
N$_o$	=	Microorganisms concentration before inactivation

For UV disinfection, the inactivation of microorganisms is directly related to UV dose; this is calculated from the product of the intensity of the light (*I*), measured in mW/cm^2 and the exposure time (*t*), measured in seconds. The UV dose is basically similar to the *CT* concept used for other common disinfectants such as chlorine and ozone. The average UV dose is calculated as *I×t*.

The *CT* concept requires monitoring and control of the ability of the chemical disinfectant contacting system (mixing, contacting and reacting steps) to provide a pre-determined level of disinfection. Disinfectants must be introduced to the contactor or contact chamber to achieve a target disinfectant residual for a desired contact time in order to satisfy *CT* requirements. The value of *C* is not equal to the disinfectant dosage injected, but the average residual disinfectant concentration (if the residual is measured at several points; otherwise it is the residual after the contactor) in the water after injection.

The contact time used in *CT* is T_{10} i.e. the length of time during which not more than 10% of the influent water would pass through that process. The use of T_{10} ensures that 90% of the water will have the required contact time. Actual T_{10} values can be significantly different from calculated hydraulic detention times (*T*) and should be determined by a tracer study, mathematical modeling or by calculations using typical baffle conditions. Table 5.2.1 summarizes the factors applicable to typical baffle conditions (AWWA 1991).

It is important to evaluate all influencing factors that could affect the *CT* required for chemical disinfection. Inefficient contact, lowered disinfectant concentrations, poor distribution and/or flow patterns in the contactor will increase the *T* requirement in the *CT* i.e. longer retention time requirements.

Table 5.2.1: Typical Baffle Conditions

Baffle Condition	T_{10}/T Ratio	Baffle Description
Unbaffled (mixed flow) separate inlet/outlet	0.1	No baffles, agitated basin, very low length to width ratio, high inlet and outlet flow velocities
Poor	0.3	Single or multiple unbaffled inlets and outlets, no intra-basin baffles
Average	0.5	Baffled inlet or outlet with some intra-basin baffles
Superior	0.7	Perforated inlet baffle, serpentine or perforated intra-basin baffles, outlet weir or perforated launders
Perfect (plug flow)	1	Very high length to width ratio (pipeline flow)

Source: AWWA 1991

In every type of disinfectant contactor, the hydraulics of water flow will govern the *CT* value as well. Approaching plug flow in the contactor will increase the ability to minimize the *T* value. The more the hydraulic regime of the disinfectant contactor approaches plug flow, the more the actual contact time approaches the hydraulic flow through time. For ozone, as very few reactors and contactors achieve plug flow condition, either a conservative *T* value should be selected or tracer testing of the contactor should be performed to determine the actual *T* at varying flow rates and at varying gas/liquid flow ratios (IOA 1990).

Water temperature, pH and water chemistry affects the disinfection requirements significantly. When a chemical disinfectant is added to water it reacts with a number of natural and synthetic organic compounds present. This creates a demand for the disinfectant in the water, which must be satisfied in order to obtain a residual concentration available for disinfection. Disinfectants also decay at a faster rate due to their reaction with organic compounds present in the water. Thus "disinfectant demand" and "decay rates" should be taken into consideration for *CT* determination. Every utility deals with a unique water matrix and each of these water matrices have their own demand and decay rates. Simple bench-scale experiments can be used to determine the chemical disinfectant demand and decay rates.

The typical ranges of the water quality characteristics for the application of alternative disinfectants are provided in Table 5.2.2. The values provided in this table are not absolute requirements but general water quality characteristic guidelines for just before the application of disinfectants, which water systems should strive to achieve. Achieving this goal will ensure that water systems will be able to apply alternative disinfectants effectively. In practical situations, conformance to some of the values in this table may not be possible. In these cases, water systems may have to either apply higher dosages of disinfectants in order to ensure an adequate level of disinfection or modify their process to meet their objective. Sometimes even when the disinfection is adequate, due to deviations in some of the values, the aesthetics of the finished water may be compromised. Hence, water systems should strive to achieve the general water quality characteristics outlined in Table 5.2.2.

**Table 5.2.2:   Typical Water Quality Characteristics for the
Application of Disinfectants**

Parameters	Chlorine	Chloramines	Ozone	Chlorine dioxide	UV
Turbidity (NTU)	≤ 1	≤ 1	≤ 5	≤ 1	≤ 1
Total Coliforms (organisms/100mL)	≤ 100	≤ 100	≤ 100	≤ 100	≤ 100
E. Coli (organisms/100mL)	≤ 20	≤ 20	≤ 20	≤ 20	≤ 20
TOC (mg/L)	≤ 4	≤ 4	≤ 4	≤ 4	≤ 4
UV transmittance (%)	NA	NA	NA	NA	≥ 75
Suspended Solids (mg/L)	≤ 10	≤ 10	≤ 10	≤ 10	≤ 10
pH	5.5 - 7.5	6.5 – 9.5	6.5 – 9.5	6.5 – 9.5	6.5 – 9.5
Colour (TCU)	≤ 15	≤ 15	≤ 15	≤ 15	≤ 5
TDS (mg/L)	≤ 650	≤ 650	≤ 650	≤ 650	≤ 650
Bromides (mg/L)	NA	NA	≤ 1 mg/L	NA	NA
Dissolved Iron (mg/L)	≤ 0.3 mg/L	≤ 0.3 mg/L	≤ 0.3 mg/L	≤ 0.3 mg/L	≤ 0.3 mg/L
Dissolved Copper (mg/L)	≤ 1 mg/L	≤ 1 mg/L	≤ 1 mg/L	≤ 1 mg/L	≤ 1 mg/L
Dissolved Manganese (mg/L)	≤ 0.05 mg/L	≤ 0.05 mg/L	≤ 0.05 mg/L	≤ 0.05 mg/L	≤ 0.05 mg/L
Odour (H_2S)	ND	ND	ND	ND	ND
Blue-Green Algae or Total microcystins (μg/L)	≤ 1.5	≤ 1.5	≤ 1.5	≤ 1.5	≤ 1.5

Note: NA=Not applicable
ND=Non-detectable

The reasons for choosing some of the parameters in Table 5.2.2 are as follows:

Turbidity: High turbidity levels can reduce the efficiency of disinfection by increasing the disinfectant demand and decay rates. The particles in water may also protect pathogens from disinfection by encasing them and preventing them from coming in contact with the disinfectants.

TOC: High *TOC* can contribute to the formation of disinfection by-products.

UV transmittance: Lower UV transmittance exerts additional stress on the UV disinfection process as the efficiency decreases significantly.

Suspended Solids: Similar to turbidity, high levels of suspended solids can protect pathogens from disinfection by encasing them and preventing them from coming in contact with the disinfectants. It can also increase the disinfectant demand and decay rates.

Colour: Colour may affect the UV disinfection performance significantly. It can also interfere with disinfectant residual measurements done by the standard analytical techniques based on colorimetric assays.

TDS: Excessive total dissolved solids may contribute to taste problems in the finished water.

Bromides: Bromides may contribute to the formation of bromate during ozonation. USEPA classified bromate as a probable human carcinogen with a maximum contaminant level of 0.01 mg/L.

Dissolved Iron, Copper and Manganese: These can contribute to taste and odour problems in the finished water.

Odour: This is important because of aesthetic reasons and customer satisfaction.

Algae: Algae levels before disinfection should be low at all times. High levels of algae will significantly reduce the disinfection efficiency by increasing disinfectant demand and decay rates and also by protecting pathogens from coming in contact with the disinfectants. High levels of algae may contribute to release of toxins. Toxins are found within the algae, which may be released during chemical disinfection. Long-term chronic exposure to microcystins or blue-green algae in drinking water may be carcinogenic to humans. The WHO established a maximum allowable guideline value for microcystin-LR of 1μg/L. A consultation document on microcystins prepared by the Secretariat of the Federal-Provincial-Territorial Subcommittee on Drinking Water recommends a maximum acceptable concentration of 1.5 μg/L for total microcystins in drinking water, based on the toxicity of microcystin-LR.

Where water quality characteristics are a concern, large drinking water systems may choose to perform some bench or pilot scale studies to gain a certain level of confidence for the selection of the design dosage of disinfectants. Though these studies can be expensive, they can prove to be extremely useful for large drinking water systems by reducing the operation and maintenance costs (Kawamura 2000). The major drawback in this exercise is the difficulty in testing the raw water or test water on a year-round basis. Before conducting any bench/pilot scale studies, the technical and economic feasibility must be assessed. For small drinking water systems bench/pilot scale studies may not be affordable. Hence, the use of conservative design is recommended.

Almost all chemical disinfectants are highly dependent on temperature. At low temperatures their effectiveness reduces dramatically. Typically in Manitoba the temperature of surface

water in winter can be as low as 0.1°C. In summer, surface water can be above 20°C. Thus, it is extremely important to record the correct temperature of the raw water before disinfection so that the appropriate dosage of the disinfectants can be delivered.

The successful application of alternative disinfectants also requires an extensive monitoring program. The location of monitoring points is very critical for a successful monitoring program. The program should be such that it represents the entire distribution system over time. Some of the critical influencing factors for determining the monitoring locations are: entry point, storage facilities, high flow areas, low flow areas, stagnant areas, pipe materials, water age, various pressure zones, and areas influenced by more than one source of water (AWWA 2001). For determining some of the critical factors such as "water age", the use of water quality modeling software like *WaterCAD* is recommended.

The frequency of monitoring varies depending on the location and the number of customers. The use of sampling frequency formulas based on the population served is the accepted practice for determining the sampling requirements. Protected groundwater supplies can be expected to require less monitoring than surface water supplies.

5.3 CHLORINE

The following section provides a brief overview of the use of chlorine in water treatment. In the past there were numerous studies done with this disinfectant and there are enormous amounts of information available in many published books (example: White, 1999; Chlorine Institute, 1996, USEPA 1999).

5.3.1 Process Chemistry

Chlorine gas reacts rapidly in water to form hydrochloric acid (*HCl*) and hypochlorous acid (*HOCl*) according to the reaction:

$$Cl_{2(g)} + H_2O \longrightarrow HOCl + H^+ + Cl^-$$

HOCl is a weak acid, which dissociates slightly into hydrogen and hypochlorite ion as:

$$HOCl = H^+ + OCl^-$$

The term "free available chlorine" is used to refer to the sum of the concentrations of molecular chlorine (Cl_2), hypochlorous acid (*HOCl*), and hypochlorite ion (*OCl⁻*). An aqueous equilibrium exists in water and is very much dependent on pH. The majority of the free chlorine is in the *HOCl* form at pH 6.0, whereas at pH 8.0 the majority exists in the *OCl⁻* form (AWWA 1999). *HOCl* is known to be more biocidally effective than *OCl⁻* form. Hence chlorine is known to be more effective at lower pH (pH 6.0).

Chlorine is also available in hypochlorite form as both aqueous solutions and dry solids. The most common aqueous hypochlorite solution is sodium hypochlorite (*NaOCl*) (approximately 12% chlorine). Gaseous chlorine tends to depress the pH while hypochlorite raises it. The reaction between sodium hypochlorite and water occurs as follows:

$$NaOCl\ +\ H_2O \longrightarrow HOCl + Na^+ + OH^-$$

The most common form of dry solid hypochlorite is calcium hypochlorite (*Ca(OCl)_2*) (approximately 6.5% chlorine). Calcium hypochlorite is formed from the precipitate that results from dissolving chlorine gas in a solution of calcium oxide (lime) and sodium hydroxide. The reaction is shown as follows:

$$Ca(OCl)_2 + 2H_2O \longrightarrow 2HOCl\ +\ Ca^{++}\ +\ 2OH^-$$
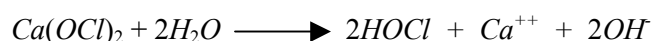
5.3.2   Disinfection and By-products

Several studies have confirmed the germicidal effectiveness of chlorine. It is extremely effective as a disinfectant against bacteria like *E. coli*, *Salmonella* and *Mycobacterium*. Chlorine is also known to be a highly effective virucide. Several studies have confirmed the efficacy of chlorine against viruses (Liu et al., 1971; AWWA 1999). Chlorine has been shown to have limited success against protozoa. It is moderately effective against *Giardia* but has little impact on the viability of *Cryptosporidium* at *CT*s typically used in water treatment.

Several environmental factors influence the inactivation efficiency of chlorine, some of which are: 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, good mixing, low pH, low turbidity, and the absence of interfering substances. Among all these factors, pH and temperature have the most impact on pathogen inactivation by chlorine (USEPA 1999). The effect of pH and temperature are described below:

pH: At higher pH (typically above 8) chlorine is less effective as a disinfectant compared to lower pH (6). The inactivation efficiency of gaseous chlorine and hypochlorite is the same at the same pH after chlorine addition.

Temperature: Pathogen inactivation by chlorine is highly dependent upon temperature. In general, for typical water treatment conditions, pathogen inactivation increases with temperature.

Chlorination results in the formation of halogenated DBPs due to the presence of NOM (natural organic matter) in the water supply. Halogenated DBPs like THMs can cause long-term health effects and hence should be removed or prevented from being formed.

Modifications to the process treatment train utilizing chlorine can be effective in reducing DBP formation. This may include moving the point of chlorination to a point after NOM removal occurs, lowering the pH using acids or coagulants, eliminating pre-chlorination for oxidation (Malcolm Pirnie, 1998), or using an alternative disinfectant.

5.3.3 Design Criteria

The *CT* values for chlorine required for the inactivation of viruses and *Giardia* at different conditions of temperature and pH are provided in Tables 5.3.1 and 5.3.2 and Figures 5.3.1 and 5.3.2. One of the major limitations of chlorine as a disinfectant is its limited ability to inactivate protozoa.

Table 5.3.1: *CT* Values (mg·min/L) for Virus Inactivation by Free Chlorine

Temperature (ºC)	Log Inactivation					
	2		3		4	
	pH		pH		pH	
	6 to 9	10	6 to 9	10	6 to 9	10
0.5	6	45	9	66	12	90
5	4	30	6	44	8	60
10	3	22	4	33	6	45
15	2	15	3	22	4	30
20	1	11	2	16	3	22
25	1	7	1	11	2	15

Source: USEPA 1999

Source: USEPA 1999

Figure 5.3.1: *CT* Values for Inactivation of *Giardia* Cysts by Free Chlorine at 10ºC (at *Cl₂* dose of 3.0 mg/L)*
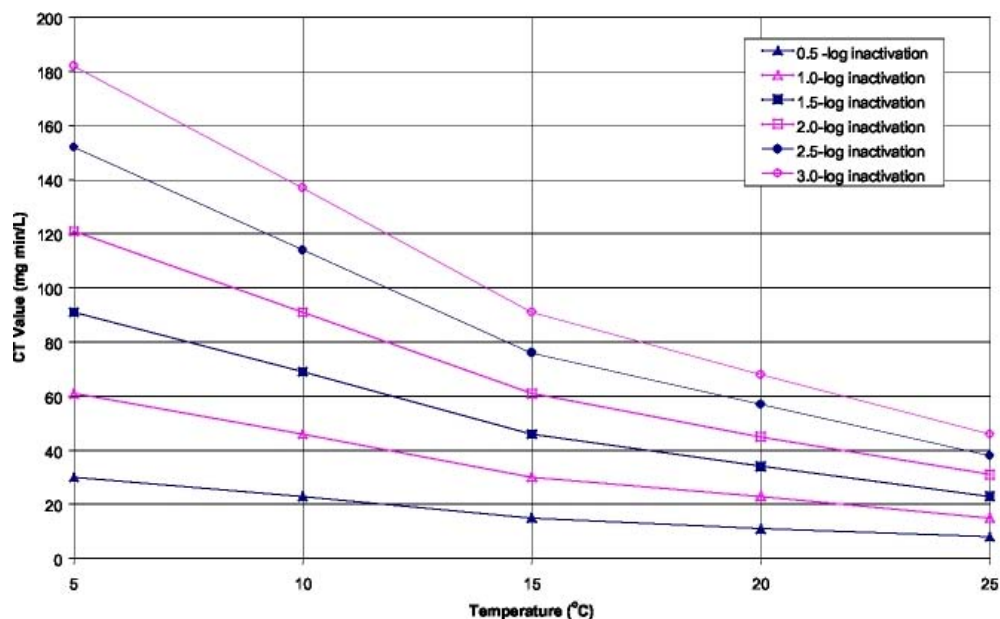
Source: USEPA 1999

**Figure 5.3.2:   *CT* Values for Inactivation of *Giardia* Cysts by Free
Chlorine at pH 7.0 (at *Cl*₂ dose of 3.0 mg/L)**

**Table 5.3.2:   *CT* Values (mg·min/L) for Inactivation of *Giardia* Cysts by Free Chlorine
at 0.5ºC or Lower**

pH	Log Inactivation					
	0.5	**1**	**1.5**	**2.0**	**2.5**	**3.0**
≤ 6	23-30	46-69	69-91	91-121	114-151	137-181
6.5	27-36	54-72	82-109	109-145	136-181	163-217
7.0	33-44	65-87	98-131	130-174	163-218	195-261
7.5	40-53	79-105	119-158	158-211	198-263	237-316
8.0	46-64	92-127	139-191	185-255	231-318	277-382
8.5	55-77	110-153	165-230	219-307	274-383	329-460
9.0	65-92	130-184	195-276	260-368	325-460	390-552

Source: MOE 2003-Amended by Earth Tech (Canada) Inc.

The resistance of *Giardia* cysts is two orders of magnitude higher than that of bacteria. The resistance is higher at low temperatures and high pH. Chlorine has very little ability to inactivate *Cryptosporidium* oocysts. The chlorine *CT* values required for *Cryptosporidium* inactivation are extremely high and may not be practically feasible. In Manitoba, every small and large drinking water system using chlorine for disinfection must maintain a free chlorine disinfectant residual of at least 0.1 mg/L at any point in the distribution system. At the point

where water enters the distribution system, a chlorine disinfectant residual of at least 0.5 mg/L must be maintained after a minimum contact time of 20 minutes under peak loading conditions.

The following are some of the design issues with chlorine as a disinfectant:

- The *CT* is an important parameter for chlorine disinfection. The required residual chlorine concentration and the contact time necessary for achieving the design *CT* values should be provided. Providing the correct *CT* values is the key towards achieving the desired level of treatment of the water.

- Water temperature has a significant effect on the efficiency of chlorine as a disinfectant. The *CT* values required for achieving a certain inactivation level should be determined after taking the temperature of the water into consideration.

- The pH of the water is also an important consideration. At lower pH chlorine is much more effective and at higher pH the chlorine dose requirement is substantially higher.

- The design of the chlorine contact chamber is also a very important consideration. Design of the contact chamber should be done to achieve a plug-flow condition as much as possible and avoid short- circuiting.

5.3.4 Generation and Operational Requirements

Chlorine may be used as a disinfectant in the form of compressed gas under pressure that is dissolved in water at the point of application, solutions of sodium hypochlorite (*NaOCl*) or solid calcium hypochlorite [$Ca(ClO)_2$]. The three forms are chemically equivalent because of the rapid equilibrium that exists between dissolved molecular gas and the dissociation products of hypochlorite compounds. 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 (USEPA 1999).

The typical process schematic layout of gaseous chlorine and hypochlorite feed system is shown in Figures 5.3.3 and 5.3.4, respectively.
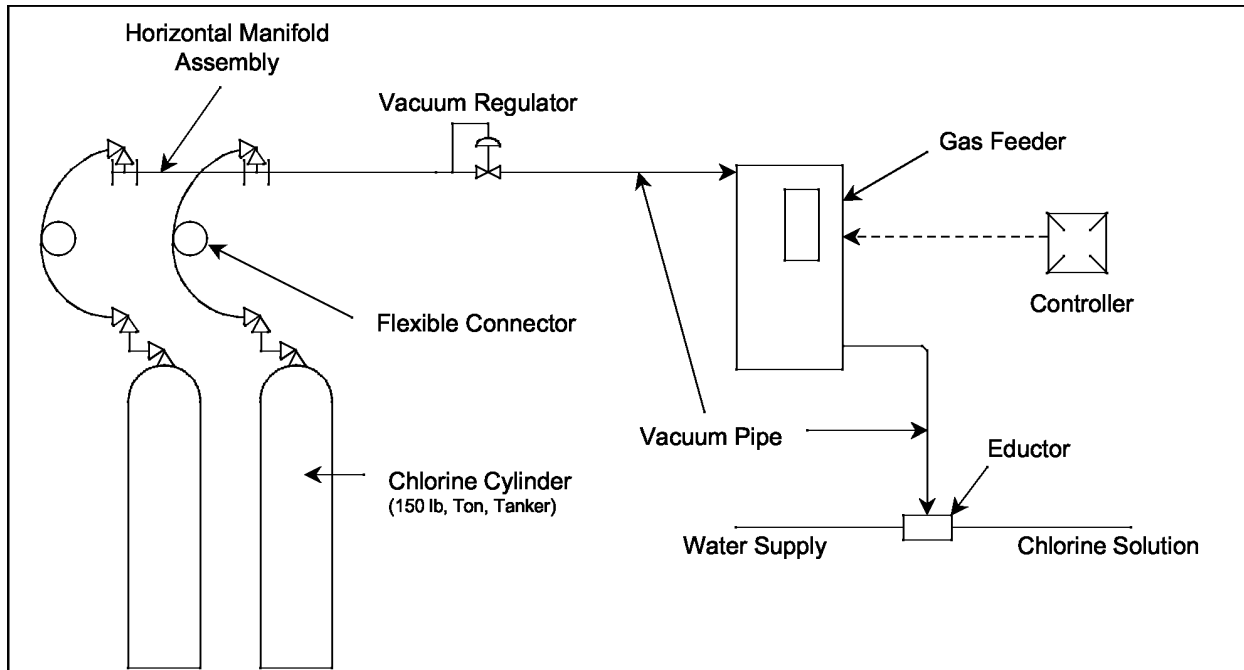
Source: USEPA 1999

Figure 5.3.3: Typical Gaseous Chlorine Feed System
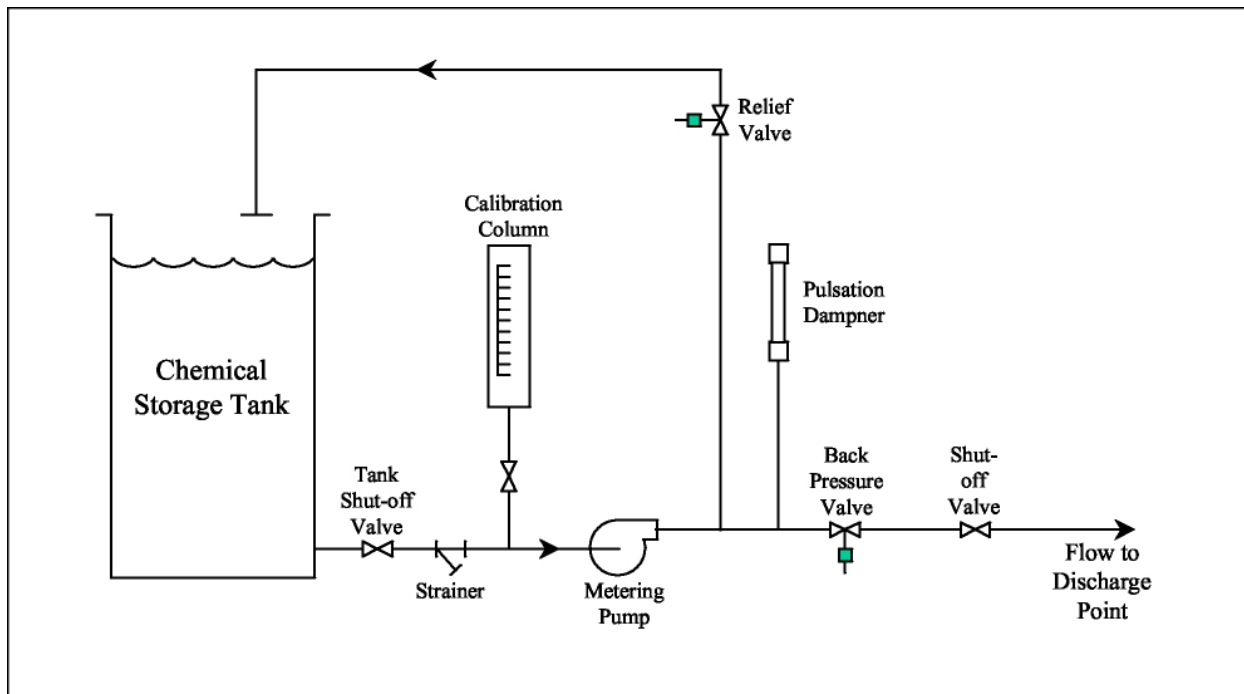
Source: USEPA 1999

Figure 5.3.4: Typical Hypochlorite Feed System

All chlorine is shipped and stored in pressure vessels as a liquefied gas under pressure, resulting in the presence of both liquid and gas phases in the containers. Cylinders are nearly

always used to feed chlorine when supplied as a gas. All cylinders must be anchored by chains for safety reasons. Chlorine cylinders are usually available in 1 ton or 150 pound cylinders. One-ton cylinders have two valves, which can supply either liquid or gas. When the valves are properly aligned in a vertical position, the upper valve feeds chlorine gas while the lower valve feeds chlorine as a liquid. For large drinking water systems, liquid chlorine must be converted to a gas by passing through a vapourizer and then into the chlorinator system. Chlorinators are designed to handle gaseous chlorine (The Chlorine Institute Inc. 1999).

There are a few major areas of concern for the operation of a gas chlorinator, including the cleanliness of the chlorine supplied and the safety of the piping system. The quality of the chlorine is important because the chlorinator feeding the gas has small orifices and fine control valves that can be clogged or plugged. Hence it is very important that the entire chlorine delivery system is kept very clean. The chlorinator has a filter at the inlet of the unit that requires periodic inspection and replacement to maintain system integrity (The Chlorine Institute Inc. 1999). Most current chlorinator installations use direct container-mounted equipment for delivery into the system. This method is the safest and most trouble-free from an operating point of view since it minimizes the use of piping or tubing carrying chlorine gas under pressure.

The chlorine gas released from the feed system is generally dissolved in water by means of a hydraulic eductor. For water supply to the eductor, a dual supply of pressurized water or a standby booster pump is required. Additionally, a device to prevent backflow should be provided (Kawamura 2000). Chlorine container storage rooms and pressure piping manifolds should be kept at a temperature that will allow the feed rates desired (The Chlorine Institute Inc. 1999). The cylinders and feeders should be located in separate rooms. Each room must have special air containment or ventilation system and leak detection equipment.

Typical commercial sodium hypochlorite is a 12% solution. Water systems often prefer to utilize sodium hypochlorite than gaseous chlorine because it is safer and easier to handle and poses fewer problems when spilled. However, a major problem with sodium hypochlorite solution is its significant loss of available chlorine (often 90 days maximum). The deterioration rate increases with higher solution strength and higher temperatures. The stability of the solution is also greatly affected by light, pH, and heavy metal cations such as iron, copper, and nickel.

Redundancy in chlorination equipment is extremely important particularly for small drinking water systems where chlorination is often the only barrier against waterborne pathogens. For gaseous chlorine, additional chlorine cylinders along with separate manifolds and gas-feeding systems are desirable. For small drinking water systems using hypochlorite, redundancy can be achieved by having an additional reliable feed pump connected to the tanks. The pump can

be used in case of an emergency when the pump for daily feeding of chlorine in water is out of order. An inventory of essential spare parts should be maintained.

5.3.5   Monitoring Requirements

The monitoring of chlorine residuals will be based on the terms and conditions of the operating licence. In general, drinking-water systems using chlorine for disinfection should monitor for free chlorine residual at least once per day before the water enters the distribution system after the minimum contact time and periodically at representative points in the distribution system. If required, water systems may be asked to install and operate continuous chlorine monitoring equipment. A free chlorine residual analyzer is an ideal device for continuous monitoring. Where the complete primary disinfection is accomplished through a series of distinct disinfection processes/steps, a continuous sample must be taken at the downstream end of each of the processes/steps. In all cases the location must be ahead of the point of addition of any post-disinfection chemicals, including those intended for the purpose of ensuring maintenance of a disinfectant residual in the distribution system or preventing corrosion in the distribution system. For water systems where continuous monitoring devices are not installed, daily monitoring using manual grab samples at the same locations must be performed. Details of chlorine residual testing and reporting requirements are available from the ODW and will be specified in operating licences. In general water systems should maintain monthly water chlorination reports, which include daily measurements of free chlorine and total chlorine residual concentrations. The purpose of this report is to summarize the data for the entire month. Measurable free chlorine residual must be maintained at all times throughout a water system. The testing for chlorine residuals will have to be done at reasonable intervals from representative points in the system.

5.3.6   Storage and Safety

The storage and safety issues of gas chlorination are very critical. Chlorine gas is a strong oxidizer and is also regarded as a toxic gas. Hence special storage and handling considerations should be considered for chlorine during the planning of a water treatment plant. Some of the safety considerations, which are of vital importance, are as follows (GOS 2004).

A written emergency plan should be prepared and workers should be trained in any of the procedures that require their involvement. All necessary equipment, supplies and competent personnel must be provided or made available. For workers working alone or in isolated places, regular contact with the administrative office should be maintained and personal protective equipment should be available.

- A chlorine alarm system with sounding alarms and warning lights should be installed and maintained where chlorine gas is used.
- A positive pressure demand type Self-Contained Breathing Apparatus (SCBA) with a full face piece, and containing a minimum 30 minute air supply, should be located

in close proximity at all installations using 68 kg or 1 tonne cylinders. The SCBA should be kept far away from the chlorine gas feed or storage room to ensure workers can put the equipment on safely. The SCBA equipment should be approved by the Occupational Health and Safety Board and the operators must be adequately trained by a competent person in the use and maintenance of SCBA through periodic refresher course.

- The operators should wear proper safety equipment when changing cylinders. The equipment consists of rubber gloves, apron and face shield or goggles.

- The employer shall provide an approved means of flushing the eyes of workers in the facility with lukewarm water or other appropriate liquid at readily accessible locations.

- Any worker who is required to enter an atmosphere immediately dangerous to life shall ensure that a second worker, suitably equipped, is present and in communication at all times with another person who is trained in handling chemical emergencies and the use of respiratory protective equipment. With this, a provision is made for rescuing the endangered worker immediately if his respiratory device fails or he becomes incapacitated for any reason.

Ideally, new gaseous chlorine facilities should be designed with enclosures and air scrubbers to capture and neutralize any gas that leaks. For existing facilities, the advantages of having a chlorine scrubber are that it leaves the existing operations mostly unchanged and it can treat any type of chlorine leak that occurs due to operator error, manifold leak, damaged cylinder from dropping it on floor, etc.

Sodium hypochlorite storage and handling procedures should be arranged to minimize the slow natural decomposition process either by contamination or by exposure to other storage conditions (GLUMRB 2003). De-gassing occurs during sodium hypochlorite decay and is a major design concern. Sodium hypochlorite solution is a corrosive liquid and spill containment must be provided for the storage tanks. Typical spill containment structures include containment for the entire contents of the largest tank, no uncontrolled floor drains, and separate containment areas for each incompatible chemical (USEPA 1999). Storage containers or tanks should be sited out of sunlight in a cool area and should be vented to the outside of the building. The use of vented ball valves is highly important. Calcium hypochlorite should be stored away from heat and organic materials that can be readily oxidized. Improperly stored calcium hypochlorite has caused spontaneous combustion fires in the past (White 1992).

5.4   CHLORAMINES

5.4.1   Process Chemistry

Chloramines are formed by the reaction of aqueous chlorine (*HOCl*) and ammonia. *HOCl* reacts rapidly with ammonia to form inorganic chloramines in a series of competing reactions (White, 1992). The reactions that occur principally are as follows:

$$NH_3 \; + \; HOCl \longrightarrow NH_2Cl \; + \; H_2O$$

$$NH_2Cl \; + \; HOCl \longrightarrow NHCl_2 \; + \; H_2O$$

$$NHCl_2 \; + \; HOCl \longrightarrow NCl_3 \; + \; H_2O$$
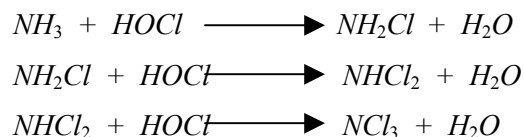
These competing reactions are primarily dependent on pH and controlled to a large extent by the chlorine:ammonia nitrogen $(Cl_2{:}N)$ ratio. The reaction between free available chlorine and free ammonia is fairly instantaneous, resulting in a combined residual or chloramines. The addition of Cl_2 to water containing NH_3 first forms monochloramine (NH_2Cl), which is the desired form of chloramines. Continued addition of Cl_2 converts the residual to dichloramine ($NHCl_2$), and then to trichloramine (NCl_3). Further addition of Cl_2 will eventually lead to the breakdown of the chloramines (breakpoint chlorination). Monochloramine (NH_2Cl) is the preferred species among the chloramines as it forms significantly less odour compared to dichloramines and trichloramines (Krasner and Barrett 1985). The optimum pH for monochloramine formation is 8. Monochloramine formation increases with decreasing $Cl_2{:}N$ ratio. The typical ratio used in water treatment is 3:1 to 5:1 (AWWA 1999).

5.4.2   Disinfection and By-products

The disinfecting properties of chloramines are not as strong as other chemical disinfectants, such as chlorine, ozone, and chlorine dioxide. Chloramines are effective as a disinfectant against bacteria in water. However, they are weaker disinfectants compared to chlorine especially for virus and protozoa inactivation. Chloramines are very stable and provide a long-lasting residual in the distribution system. Chloramine species such as monochloramine have been shown to be very effective in controlling biofilms because of its superior ability to penetrate the biofilms.

Chloramines form much lower levels of by-products than chlorine. Chloramines have been shown to reduce the formation of THMs and other DBPs by about 80 percent. However, the effectiveness of chloramines to control DBPs depends on a number of factors such as the chlorine-to-ammonia ratio, the point of addition of ammonia relative to that of chlorine, the extent of mixing and pH. Inability to react chlorine and ammonia instantaneously allows free chlorine to react with other compounds to form harmful by-products.

Recently, *NDMA* (*N*-nitrosodimethylamine) was identified to be one of the disinfection by-products formed during chloramination. It is identified as a carcinogen by California's Proposition 65 and as a probable human carcinogen by the USEPA (Liang et al. 2003). There is currently no Maximum Contaminant Level for *NDMA* in drinking water, nor has the USEPA established a health advisory for *NDMA* in drinking water. In December 1999, the California Department of Health Services (CDHS) set an initial *NDMA* action level in drinking water at 20 ng/L. In March 2002, the temporary action level was revised to 10 ng/L (Liang et al. 2003). Action levels considered by CDHS are advisory levels and not enforceable

standards. Commercial cationic polymers exhibit *NDMA* formation potential with chloramines. Little information is available on treatment methods for *NDMA* in water but pulsed UV has shown some potential. It is generally believed that UV light can be effective in destroying *NDMA* by breaking the nitrogen-nitrogen bond in the molecule. However, it can lead to the formation of undesirable chemicals as reaction intermediates (Liang et al. 2003).

5.4.3   Design Criteria

The *CT* values required for achieving *Giardia* cyst and virus inactivation using chloramines are shown in Tables 5.4.1, 5.4.2 and 5.4.3, respectively (USEPA 1999). The *CT* requirements of chloramines depend on a number of factors such as pH, temperature, and organic nitrogen in the water. pH impacts the disinfection efficiency mainly by controlling the chloramine species distribution. In general, the impact of pH on chloramine disinfection efficiency is less compared to chlorine. The bacterial and viral inactivation rate of chloramines increases with temperature and dramatically decreases with lower temperature. Water containing high levels of organic nitrogen reacts with chloramines to form by-products such as organic chloramines. Organic chloramines have very little biocidal and virucidal properties and hence they are undesirable.

Table 5.4.1: *CT* Values for *Giardia* Cyst Inactivation Using Chloramines

Inactivation (log-units)	*CT* (mg·min/L)				
	5ºC	**10ºC**	**15ºC**	**20ºC**	**25ºC**
0.5	365	310	250	185	125
1.0	735	615	500	370	250
1.5	1,100	930	750	550	375
2.0	1,470	1,230	1,000	735	500
2.5	1,830	1,540	1,250	915	625
3.0	2,200	1,850	1,500	1,100	750

Source: USEPA 1999.

Values shown in this table are based on a pH range between 6 and 9.

Table 5.4.2: CT Values for Virus Inactivation Using Chloramines

Inactivation (log-units)	*CT* (mg·min/L)				
	5ºC	**10ºC**	**15ºC**	**20ºC**	**25ºC**
2	857	653	428	321	214
3	1,423	1,067	712	534	356
4	1,988	1,491	994	746	497

Source: USEPA 1999

Table 5.4.3: *CT* Values (mg·min/L) for *Giardia* Cyst and Virus Inactivation Using Chloramines at ≤ 1°C Between pH 6 to 9

Pathogens	Log Inactivation			
	1.0	**2.0**	**3.0**	**4.0**
Giardia Cyst	1270	2535	3800	-
Virus	-	1243	2063	2883

Source: MOE 2003

In Manitoba, a water system approved to use chloramines for disinfection of groundwater must maintain a monochloramine disinfectant residual of at least 0.3 mg/L at any point in the distribution system. At the point where water enters the distribution system, a monochloramine disinfectant residual of at least 1.0 mg/L must be maintained after a minimum contact time of 20 minutes under peak loading conditions.

5.4.4 Generation and Operational Requirements

Chloramines are generated by the sequential addition of chlorine (hypochlorous acid) and ammonia at a Cl_2 to NH_3 ratio ranging from of 3:1 to 5:1. Either chlorine or ammonia may be added first. Chlorine is normally added first to act as the primary disinfectant (particularly for virus inactivation) and after 2 to 30 minutes, ammonia is added to prevent further formation of DBPs. The most common methods of chlorine addition include gas feed using a dilution water eduction system or direct feed of sodium hypochlorite solution (12 percent typical commercial strength) (USEPA 1999).

Ammonia can be fed either as gaseous (anhydrous ammonia) or liquid (aqueous) ammonia or ammonium salts such as ammonium sulfate. Typical schematics of ammonia feed systems are shown in Figures 5.4.1 to 5.4.3. Anhydrous ammonia is usually stored in portable cylinders or stationary tanks. In Manitoba, the storage tanks should be located indoors and should be protected from extreme temperatures. Aqueous ammonia is produced commercially by dissolving anhydrous ammonia into deionized water or softened water. The aqueous ammonia is stored in low-pressure tanks, typically made of steel or fiberglass. Excessive temperatures can cause ammonia gas to vapourize so each storage tank should be equipped with a water trap or ammonia scrubber to keep vapours from escaping to the atmosphere. When aqueous ammonia is applied to the water, complete mixing is required for the ammonia to react with chlorine in the water to reduce formation of dichloramine and nitrogen trichloride (USEPA 1999).
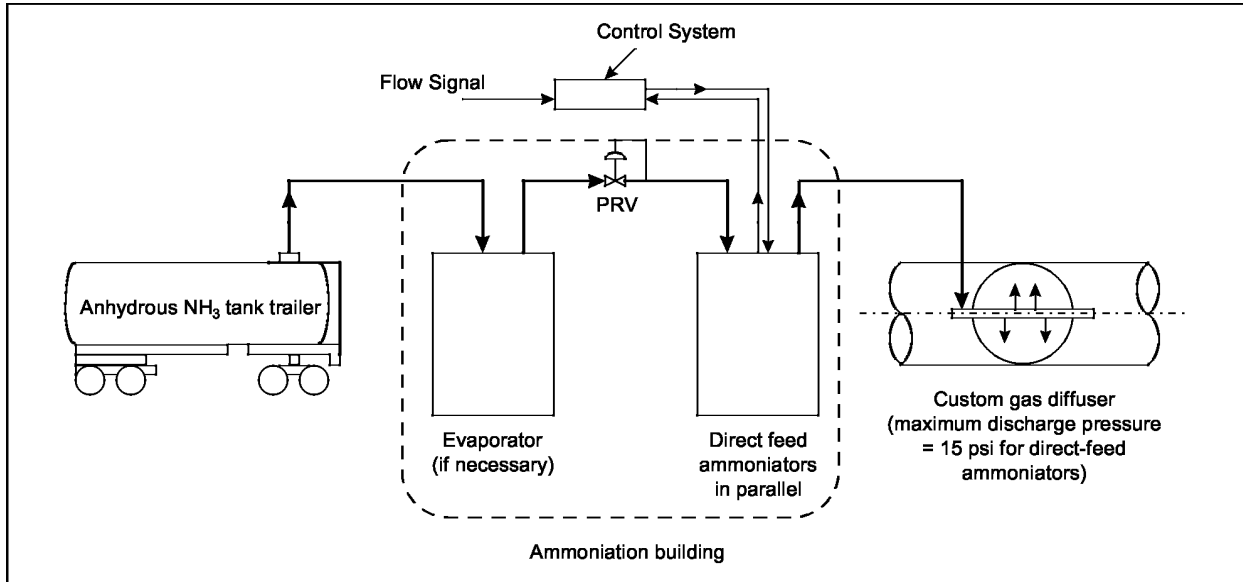
Source: Montgomery, 1985.

Figure 5.4.1: Anhydrous Ammonia Direct Feed System
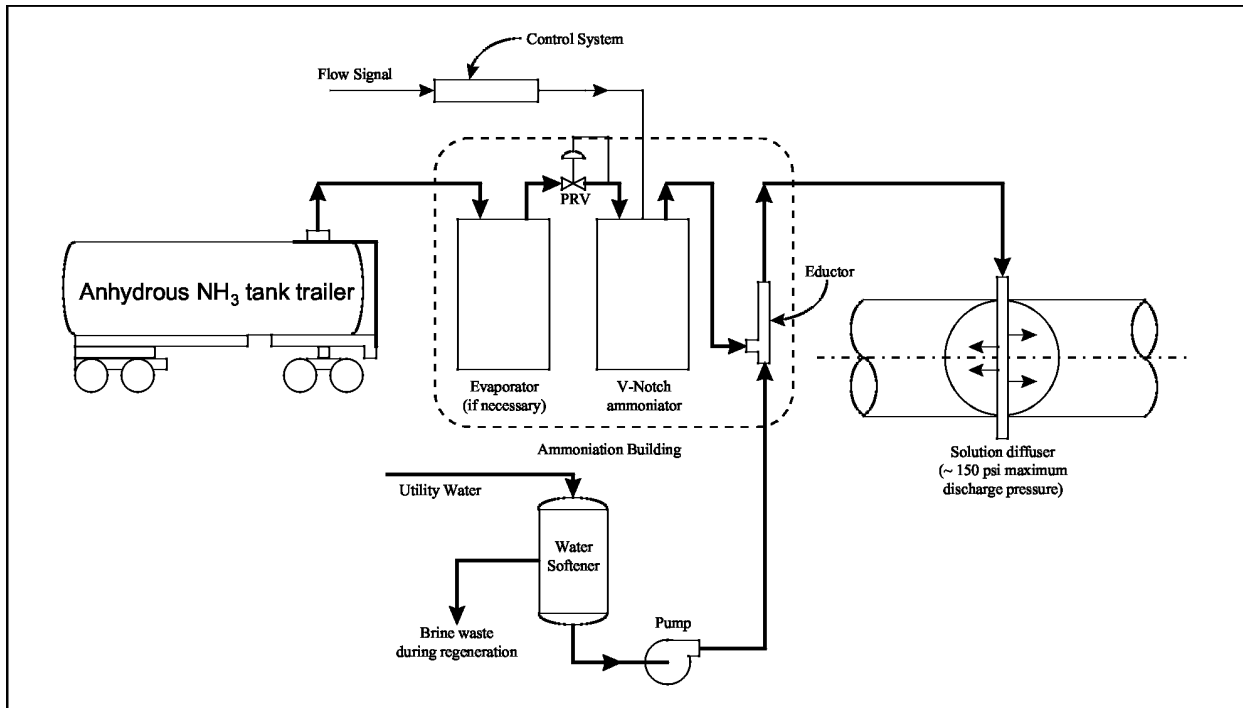
Source: USEPA 1999

Figure 5.4.2: Anhydrous Ammonia Solution Feed System
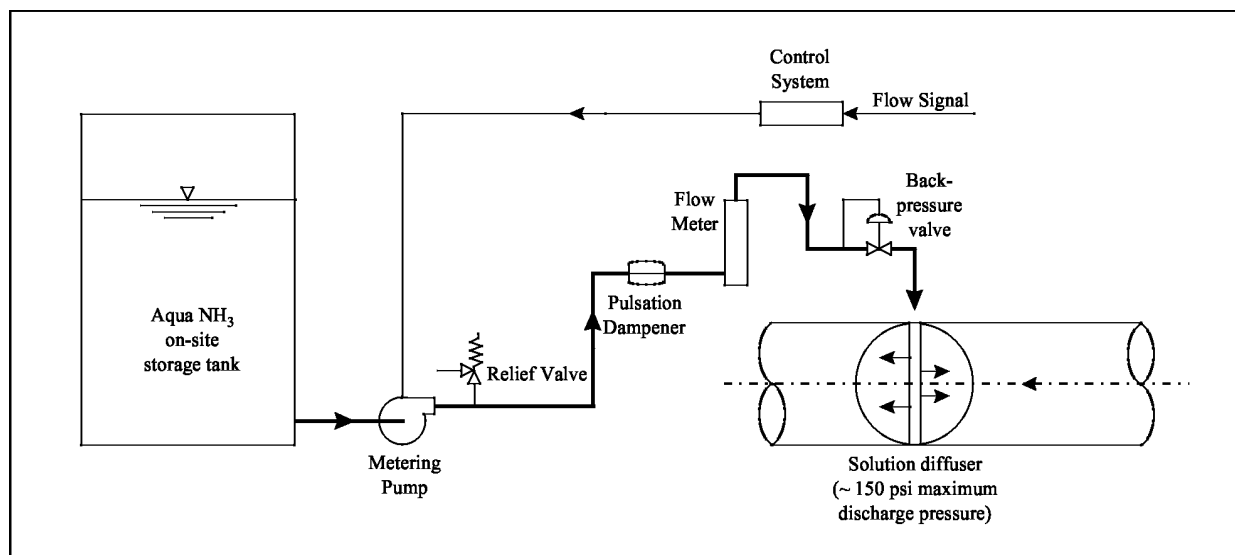
Source: USEPA 1999

Figure 5.4.3: Aqua Ammonia Feed System

The use of ammonia in gas form should be limited to cylinder deliveries. Except for very large drinking water systems, the use of storage tanks or railcars or tanker trucks are not recommended due to safety concerns. Solution-feed ammoniators are more common. The major disadvantage of a solution-feed ammoniator is the formation of ammonium hydroxide due to the reaction with hardness in water. Thus the injector water should be softened to a certain level of hardness to prevent the injector from plugging because of hardness scaling (White 1999).

For anhydrous ammonia, the typical piping materials for both direct and solution feed systems are stainless steel, PVC, and black iron (Dennis et al., 1991). Stainless steel or black iron pipe is used in the high-pressure (i.e., greater than 15 psi) portions of the feed system. PVC pipe is used only in the low-pressure portion of the feed system, after the ammoniators. For aqueous ammonia, PVC piping should be used due to the corrosive nature of aqueous ammonia (Dennis et al. 1991).

The solution lines should be sized such that the system does not exceed 0.45 m of total head loss. The diffusers should be designed with holes that will create a head loss of approximately 2.4 m to 3.4 m. Overall the turbulence should be sufficiently large for a quick mix (White 1999).

Redundancy of chloramination facilities is highly desirable. At a minimum, the water system should have an additional pump for delivering the hypochlorite to the water in case of an emergency. For gaseous ammonia, a minimum of two ammonia feeders is recommended such that one can be kept as a standby. The storage tanks should be able to hold a minimum of

15 days supply. When the ammonia feeders are not working, until they are operational, hypochlorites alone can be used to treat the water in the form of chlorine.

One of the major potential operational impacts of chloramination is "nitrification". Nitrification occurs when there is an excess of ammonia present in the distribution system. Ammonia can promote the growth of nitrifying bacteria. The excess ammonia acts as a nutrient and supports the growth of nitrifying bacteria, which convert the excess ammonia to nitrites and nitrates (USEPA 1999). The presence of nitrite indicates biological activity is occurring and is essential for a "real-time" measure of nitrification. Complete nitrification occurs when nitrate is produced. Nitrification can rapidly reduce free chlorine, accelerate decomposition of chloramines, and can interfere with the measurement of free chlorine (Skadsen 1993). Loss of chlorine residual allows an increase in HPC bacteria and potentially increases the total coliform levels (Cowman and Singer 1994). Hence, nitrification should be assessed and controlled at all times.

Some of the recommended approaches for controlling nitrification are as follows (USEPA 1999):

- Decreasing the detention time
- Increasing the pH
- Decreasing the TOC concentration
- Increasing the chloramines residual
- Increasing the chlorine-to-ammonia ratio
- Decreasing the excess ammonia concentration

Some source waters naturally have high levels of ammonia, particularly for some wells and groundwater. Ammonia in source waters is derived mainly from organic sources or as a waste by-product from feedlots, fertilizers, and wastewater. For those water systems planning to use chlorine as a primary disinfectant, high levels of ammonia well create a huge chlorine demand, thus making breakpoint chlorination difficult. In such cases maintaining chloramines may be more economical because there is no need to add enough chlorine to reach breakpoint. However, chloramines as a primary disinfectant must be able to provide the required protection of the water against pathogens. If the ammonia levels in the source water fluctuate from low to high, the level of ammonia should be monitored frequently to establish a baseline. When that can be done, a decision can be made whether to continue chloramination or breakpoint chlorination. For breakpoint chlorination, the water treatment plant operator must determine the site-specific breakpoint curve. The end chlorine dosage depends on the water supply, seasonal variations, water temperature, and pH. The other option would be to remove the ammonia, which would require the installation of a treatment process such as reverse osmosis, ion exchange, electrodialysis, biological denitrification, or lime softening (Angers 2002). More often pH adjustment and aeration is the cheapest way to go.

5.4.5   Monitoring Requirements

The purpose of a monitoring program for chloramination is to ensure that water quality objectives are met, to gain an understanding of how the water quality of the system behaves in response to seasonal water quality changes and process upsets, to anticipate possible challenges (i.e. nitrification or re-growth) and for regulatory compliance (AWWA 2001). Some of the key monitoring parameters for chloramination are as follows (AWWA 2001):

Monochloramine Residual: For monochloramine measurement, the traditional method of subtracting the free chlorine residual from the total chlorine residual assumes that the formation of other chlorine species is negligible. The direct measurement of monochloramine developed by *Hach* is a very convenient method for determining monochloramine residual in water systems. In this method (Method 10171), the formation of green-coloured indophenol is directly proportional to the amount of monochloramine present in the sample.

Total Chlorine Residual: Total chlorine residual consists of monochloramine, dichloramine, nitrogen trichloride and organic chloramines, and free chlorine. According to the breakpoint curve, at chlorine to ammonia-N ratios of 5:1 or less, the predominant species is monochloramine. Distinction between the chlorinated species is not required. A decrease in total chlorine residual is an indication of the possible onset of nitrification in the system.

Free Chlorine Residual: The free chlorine residual test can be used to determine if the chlorine to ammonia ratio is too high at a treatment plant. If ammonia is underfed, free chlorine residual can be detected since the breakpoint chlorination curve is time dependent.

Ammonia-N: Ammonia-N is the ammonia combined with chlorine in the various chloramine species as well as the free ammonia in the solution. The monitoring of ammonia-N is essential to evaluate or adjust the chlorine to ammonia-N ratio (AWWA 2001).

Nitrite-N: It is important to consider the concentration of nitrite for nitrification control in the distribution system. The presence of nitrite indicates biological activity is occurring and is essential for a "real-time" measure of nitrification. Complete nitrification occurs when nitrate is produced.

Heterotrophic Plate Count (HPC): The HPC is used as a surrogate for biological activity in the water system since the test of ammonia oxidizing bacteria is complex and time consuming. Several tests are available for HPC, among which the test using R2A agar is considered to be the most popular.

pH: A decrease in pH in the distribution is an indication of nitrification.

Temperature: Storage facilities such as stand pipes or elevated storage tanks can experience temperature variations, which create "stratification". Stratification inhibits mixing within a

tank or reservoir, which often results in the decay of chlorine and the onset of nitrification within the storage facility.

In general, the conditions favouring nitrification include warm temperatures, excess ammonia, low chlorine-to-ammonia ratio, low chloramines dose, and long detention times. Some of the indications of a nitrification episode include a loss or decrease in chlorine residual, increase in nitrite, increase in HPC bacteria, loss of free ammonia, decrease in dissolved oxygen levels, and/or an increase in taste and odour problems. An increase in total coliforms is not always observed during a nitrification episode.

Water systems that have converted from chlorine to chloramines for disinfection should implement an enhanced monitoring program. The purpose of the enhanced monitoring program is to monitor water quality during and after conversion to chloramines, and more specifically to ensure that residuals are maintained across the system and to identify locations where nitrification or re-growth may occur.

5.4.6   Safety

There are several safety precautions for chloramines generation, some of which are as follows (Dennis et al. 1991):

- Chlorine and ammonia gas should never be stored in the same room
- Ammonia gas application points should be located at least 5 feet away from chlorine feed solution lines
- For ammonia, ventilation and vapour detection devices should be located at high points in the room when the storage tanks and/or chemical feed equipment are installed indoors. For gaseous chlorine these should be located at low points since chlorine is heavier than air.
- Ammonia gas storage tanks should always be protected from direct sunlight or direct sources of heat to avoid pressure increases in the tank.
- Fume control may be required for mitigating the risk of fugitive emissions of ammonia
- An emergency scrubber system may also be required to reduce the risk of accidental release from a storage container
- Due to cold climates in Manitoba, outdoor storage of aqueous ammonia is not recommended

5.5   OZONE

Ozone is a powerful oxidant, which has several advantages over other disinfectants. Generally ozone achieves much higher degrees of disinfection with relatively less concentration and contact time compared to other chemical disinfectants. It also does not form any halogenated by-products such as trihalomethanes. However, other by-products such as brominated DBPs and aldehydes can be formed. Ozone degrades rapidly over time and fails to provide a lasting

residual in the distribution system. Hence, ozone should always be followed by a secondary disinfectant such as chlorine or chloramines.

5.5.1   Disinfection and By-products

In general ozone has a high germicidal effectiveness against a wide range of pathogenic organisms including bacteria, protozoa, and viruses. Several studies were done with ozone in the past some of which are as follows:

- Wuhrmann and Meyrath, 1955: 4 log reduction of *E. coli* levels in less than 1 minute with a ozone residual of 9 mg/L at a temperature of 12ºC.

- Domingue et al. 1988: Greater than 2 log reduction of *Legionella pneumophila* with a minimum contact time of 5 minutes at an ozone concentration of 0.21 mg/L.

- Wickramanayake et al. 1984a and 1984b: 2 log inactivation of protozoan cysts like *Giardia lamblia* and *Giardia muris* were obtained at 0.53 and 1.94 mg·min/L at 5ºC, respectively and 0.17 and 0.27 mg·min/L at 25ºC, respectively at pH 7.

- Keller et al. 1974: More than 3 log inactivation of poliovirus 2 and coxsackie virus B3 was obtained with ozone residual of 0.8 mg/L and 1.7 mg/L respectively, at a contact time of 5 minutes.

- Korich et al. 1990: 2 log inactivation of *Cryptosporidium parvum* was obtained with an ozone *CT* of 5 to 10 mg·min/L at 25ºC.

- Langlais et al. 1990: 2 log inactivation of *Cryptosporidium baileyi* was obtained for an ozone *CT* of 2.4 to 3.2 mg·min/L at 25ºC.

- Finch et al. 1994: 2 log inactivation of *Cryptosporidium parvum* was obtained for an ozone residual of 0.5 mg/L for about 5 minutes in buffered laboratory water at 22ºC.

- Gyürék et al. 1999: 2 log inactivation of *Cryptosporidium parvum* was obtained at 4.4 to 4.9 mg·min/L at 22ºC between pH 6 to 8 in buffered laboratory water.

- Oppenheimer et al. 2000: 2 log inactivation of *Cryptosporidium parvum* was obtained at 22 to 52 mg·min/L at 5ºC and 1.2 to 2.9 mg·min/L at 22ºC between pH 6.2 to 8.2 in natural waters.

- Li et al. 2001: 2 log inactivation of *Cryptosporidium parvum* was obtained at 42 to 43 mg·min/L at 1ºC and 4.6 to 4.7 mg·min/L at 22ºC between pH 6 to 8 in buffered laboratory water.

Protozoan cysts are much more resistant to ozone than vegetative forms of bacteria and viruses. The protozoan parasite *Cryptosporidium* is more resistant to ozone (Peeters et al., 1989; Langlais et al., 1990) than any other protozoan parasites. Hence, the *CT* requirements for inactivation of *Cryptosporidium* are the highest among most of the waterborne pathogens.

Ozone does not form any halogenated DBPs such as trihalomethanes and haloacetic acids but it does form a variety of organic and inorganic byproducts. If bromide ions are present in the raw water, brominated DBPs may be formed. These brominated DBPs pose a greater health risk than non-brominated DBPs (USEPA 1999). The Guidelines for Canadian Drinking Water Quality established an interim maximum acceptable concentration (IMAC) level of 10µg/L for bromate. USEPA (1999) reported that bromate ion formation is an important consideration for

waters containing more than 0.10 mg/L bromide ion. Byproducts such as aldehydes, ketones, acids, and others will also be formed upon ozonation of water. The primary aldehydes that have been measured are: formaldehyde, acetaldehyde, glyoxal, and methyl glyoxal (Glaze et al., 1991).

The application of ozone may be limited for source waters containing bromide ion. Studies (Song et al., 1997) have shown that bromate ion and brominated organics can be controlled during ozonation by the following techniques (USEPA 1999):

- Low pH decreases bromate ion formation and increases brominated organic formation
- Ammonia addition with short ozone contact time decreases both bromate ion and brominated organic formation
- Hydrogen peroxide decreases brominated organic formation and may increase or decrease bromate ion formation, depending on other water quality parameters
- Low ozone: *TOC* ratio leads to low bromate ion and brominated organic formation

5.5.2 Design Criteria

There is significant information available in a number of guidance manuals (USEPA 1991, 1999, 2003a) published by the USEPA providing a description of how to calculate the *CT* values for ozone and the methods for determining the residual ozone concentration (*C*) and contact time (*T*). Figures 5.5.1 and 5.5.2 show the *CT* values for the inactivation of *Giardia* and viruses by ozone at different conditions. The *CT* table for the inactivation of *Cryptosporidium* oocysts using ozone at different temperatures is provided in Tables 5.5.1 and 5.5.2.

The pH of water is not significantly dependent on the microbial inactivation kinetics, but there is a strong impact of pH on ozone demand and decay rate. With an increase in pH, the initial ozone demand and decay rate increase substantially (USEPA 2003a).

The *CT* requirement for ozone disinfection is a function of temperature. As the temperature decreases, the *CT* required to achieve a given level of inactivation increases. Conversely, as the temperature increases, the *CT* required to achieve a certain level of inactivation decreases. The ozone dosage required at lower temperatures is substantially higher than at higher temperatures. Manitoba experiences low temperatures during a significant portion of the year. As such determination of accurate *CT* by taking into consideration the low temperatures is very important for ozone systems to perform effectively.
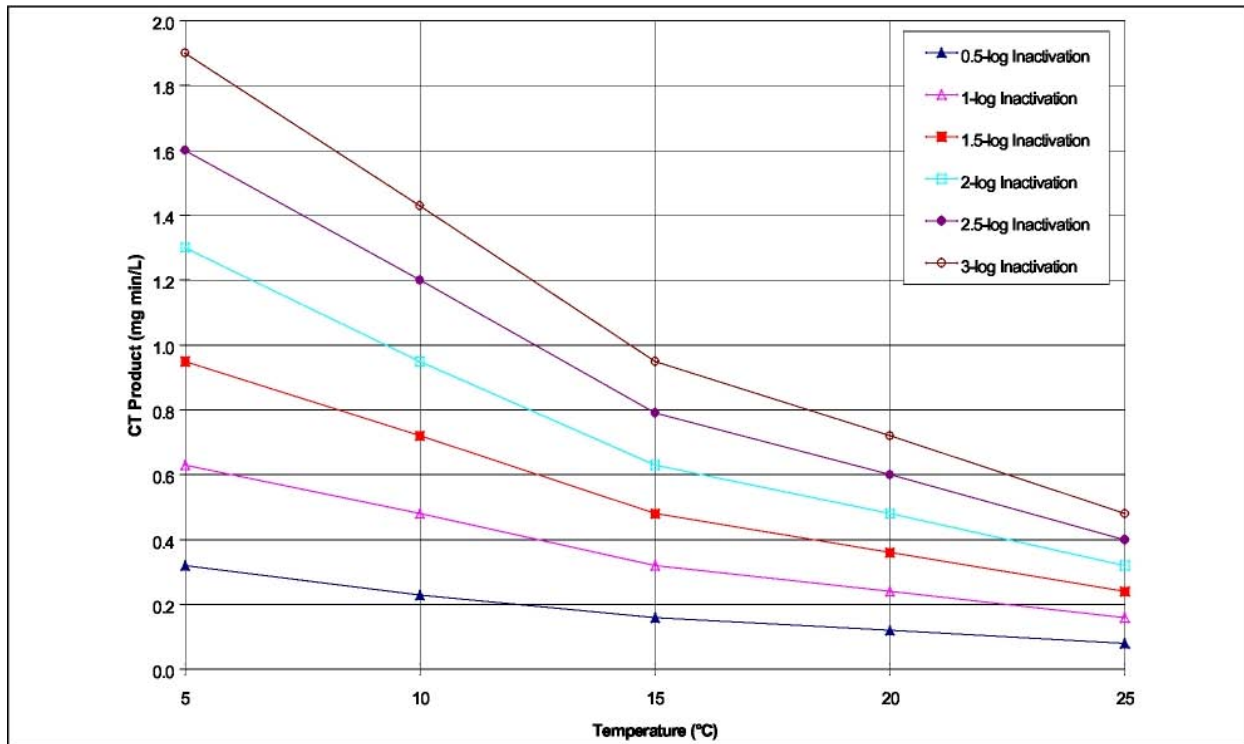
Source: USEPA 2003a

Figure 5.5.1: *CT* Values for Inactivation of *Giardia* Cysts by Ozone (pH 6 to 9)

For all ozone applications in water treatment, bench scale studies should be conducted to determine minimum and maximum ozone dosages for disinfection *CT* compliance and oxidation reactions. Pilot scale studies should be conducted for all surface waters to document benefits and DBP precursor removal effectiveness. Determination of accurate results during the bench and pilot scale studies is very crucial. Some of the sensitive measurements include gas flow rate, water flow rate, and ozone concentration (GLUMRB 2003).

It should be noted that ozone can never be used as a stand-alone treatment for any utility. This is because ozone cannot provide the residual protection in the distribution system to prevent microbial growth. Ozone decays very rapidly (within minutes) and hence it disappears from the water very fast. In order to provide the residual protection, ozonation should be followed by a secondary disinfectant, such as chlorine or chloramines, which is stable and can provide the necessary residual protection in the distribution system.
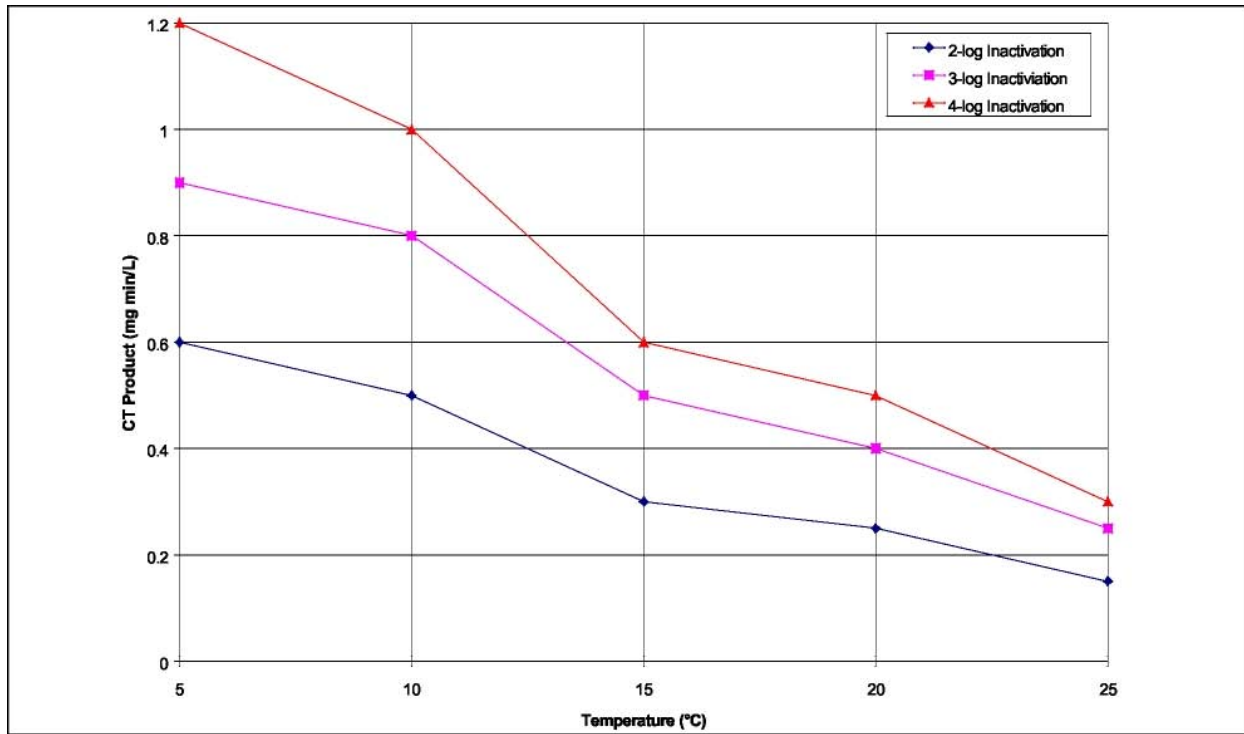
Source: USEPA 2003a

Figure 5.5.2: *CT* Values for Inactivation of Viruses by Ozone (pH 6 to 9)

Table 5.5.1: *CT* Values (mg·min/L) for *Cryptosporidium* Inactivation by Ozone

Log credit	Water Temperature, ºC									
	≤ 0.5	1	2	3	5	7	10	15	20	25
0.5	12	12	10	9.5	7.9	6.5	4.9	3.1	2.0	1.2
1.0	24	23	21	19	16	13	9.9	6.2	3.9	2.5
1.5	36	35	31	29	24	20	15	9.3	5.9	3.7
2.0	48	46	42	38	32	26	20	12	7.8	4.9
2.5	60	58	52	48	40	33	25	16	9.8	6.2
3.0	72	69	63	57	47	39	30	19	12	7.4

Source: USEPA 2003a

Table 5.5.2: *CT* Values (mg·min/L) for *Giardia* Cyst and Virus Inactivation Using Ozone at ≤ 1°C between pH 6 to 9

Pathogens	Log Inactivation			
	1.0	2.0	3.0	4.0
Giardia Cyst	0.97	1.9	2.9	-
Virus	-	0.9	1.4	1.8

Source: MOE 2003

5.5.3   Generation and Operational Requirements

Ozone used in water treatment systems requires four basic components: a gas feed system, an ozone generator, an ozone contactor, and an off-gas destruction system. A simplified schematic of an ozone system is shown in Figure 5.5.3. The gas feed system can be either air or high purity oxygen or a mixture of the two. The basic purpose of the gas feed system is to provide a clean and dry source of oxygen to the generator. Air feed systems for ozone are fairly complicated as the air should be properly conditioned to prevent damage to the generator. The air should be clean, dry and free of contaminants.

Ozone can be generated by a number of methods but the most popular is the corona discharge process. In an ozone generator, a significant portion of the electrical energy input is lost as heat. Due to the rise in temperature during the production of ozone, adequate cooling arrangements are necessary in order to maintain the generator efficiency (IOA 1990).
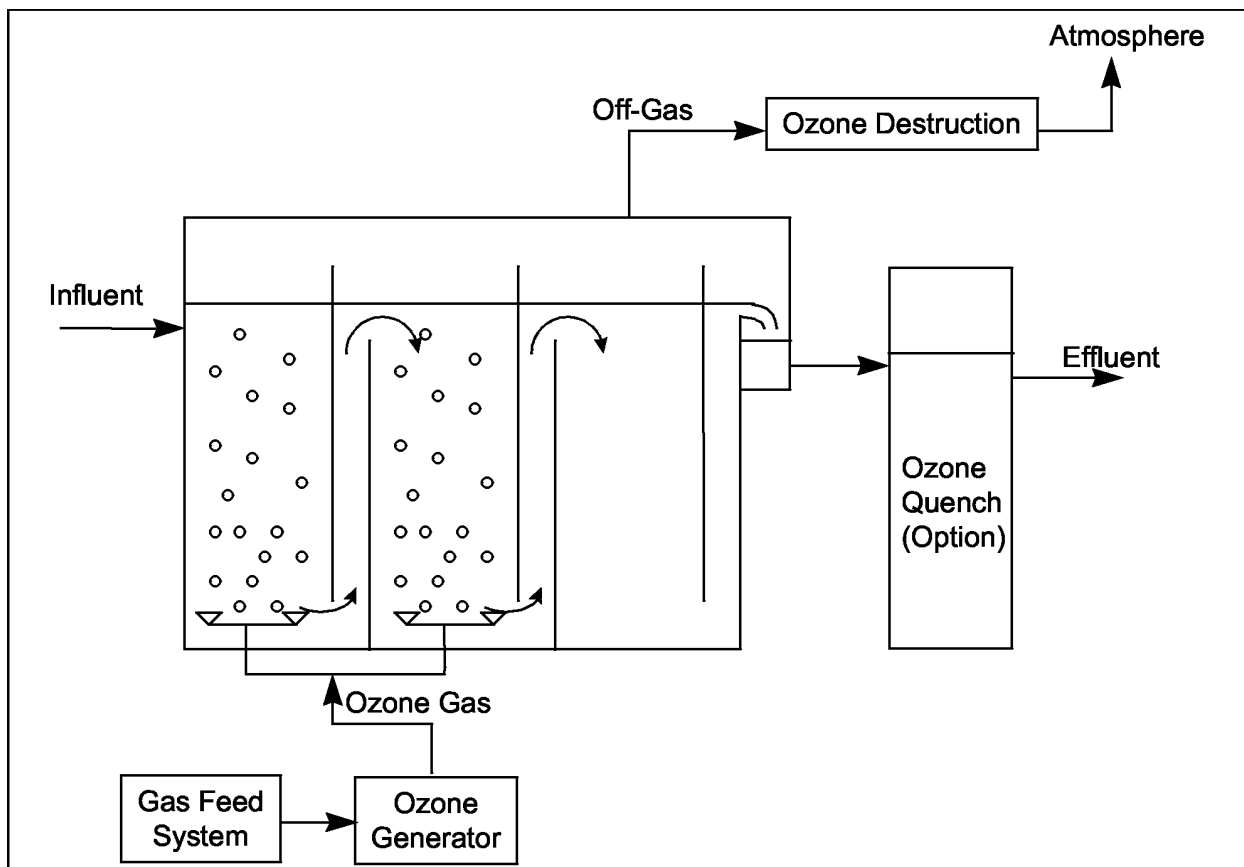
Source: USEPA 1999

Figure 5.5.3: Simplified Ozone System Schematic

Once ozone is generated, it needs to be transferred to water using ozone contactors. In general, contactor design should emphasis ozone transfer efficiency. Due to the variability in ozone's reaction rate with various water contaminants, any preliminary contactor selection should be

based on process modeling and, wherever possible, actual pilot plant testing with direct scale-up of process conditions. Common ozone dissolution methods are bubble diffuser contactors, injectors, static mixers, and turbine mixers. Bubble diffuser contactors are the most widely used technology with proven levels of performance. Key elements in the design of contactors are as follows (IOA 1990):

- Minimum water depth of 5.5m
- Height:Width:Length ratio of 1.5:1.0:1.0
- Minimum vent gas collection space of 2.5 feet or a freeboard of 3 feet
- Baffling to maximize plug flow and minimize short circuiting
- Flow pattern and number of contact steps required
- Design for gas-tight construction
- Gas/liquid ratios typically ranging from 0.2 to 0.5
- Diffuser layout

Contactor dimensions should be based on retention time, design operating temperature and diffuser specifications to achieve required transfer levels (IOA 1990).

The other common ozone contactor is the side-stream ozone injection system. In this system ozone is injected into a water stream under negative pressure, which is generated in a venturi section, pulling the ozone into the water stream. In many cases, a sidestream of the total flow is pumped to a higher pressure to increase the available vacuum for ozone injection. After the ozone is injected into this sidestream, the sidestream containing all the added ozone is combined with the remainder of the plant flow under high turbulence to enhance dispersion of ozone into the water. Figure 5.5.4 illustrates the typical in-line and side-stream ozone injection systems (USEPA 1999).

The gas to liquid ratio is a key parameter used in the design of injector contacting systems. This ratio should be less than 0.067 cfm/gpm to optimize ozone transfer efficiency (Langlais et al., 1991). Meeting this criterion typically requires relatively low ozone dosages and ozone gas concentrations greater than 6 percent by weight (DeMers and Renner, 1992). High concentration ozone gas can be generated using a medium-frequency generator and/or liquid oxygen as the feed gas (USEPA 1999).
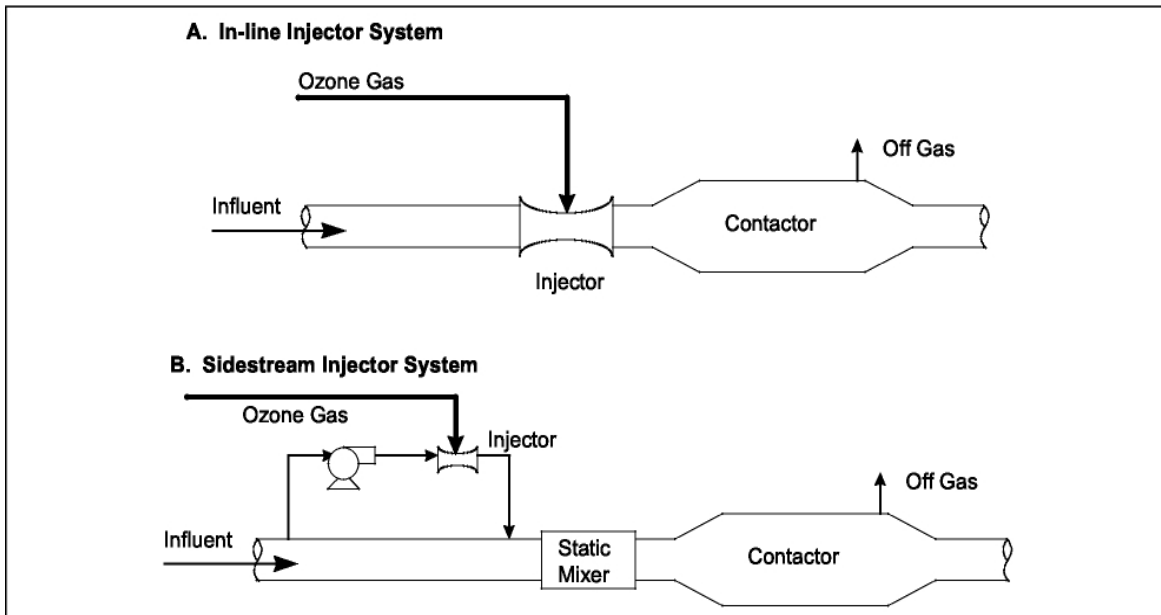
Source: USEPA 1999

Figure 5.5.4: Side-stream Ozone Injection System Schematic

To meet the *CT* disinfection requirements, additional contact time is required after the injector, typically in a plug flow reactor. The additional contact volume is determined in conjunction with the applied ozone dosage and estimated residual ozone concentration to satisfy the disinfection *CT* requirement (USEPA 1999).

The concentration of ozone in the off-gas from the contactor is usually very high (USEPA 1999). Due to the hazardous and corrosive nature of ozone, even in low concentrations, no ozone-containing gas should be allowed to escape the ozone contactor. Ozone contactors and reactors should be designed to capture all residual gases and vent these gases to an ozone destruction process, which will destroy the residual ozone before releasing the treated gas to the environment (IOA 1990).

Ozone destruction is usually achieved through an ozone collection step, followed by an ozone destruction step using a catalytic converter. The collection step involves capturing all gases from the ozone contactor released after contact with the liquid and reducing any foam or particulate matter as well as volume of moisture through the use of demisters and foam suppressant sprays. After demisting the gas, flow should continue to the ozone destruct unit. Typically, ozone destruction units convert ozone to environmentally safe oxygen.

Canada requires ozone level to be restricted to 82 parts per billion in any one-hour period under the National Ambient Air Quality Standards. Since 1989, this objective has been enforced at the federal and provincial levels.

Even in the most efficient ozone contactors, a residual amount of ozone can be released into the vent gases. Removing this ozone is essential. In the United States, the OSHA standard allows for a Permissible Exposure Level (PEL) not to exceed 0.1 ppm of ozone, time-weighted average over 8 hours per day, five days per week, with a maximum single exposure level of 0.3 ppm. Thus the ozone destruct system should ensure that the vent gases do not contain in excess of 0.1 ppm of ozone (IOA 1990).

Redundancy of ozonation equipment is essential for large drinking water system especially for continuous flow systems. However, redundancy can be compromised when it can be demonstrated that if the ozone equipment fails the secondary disinfectant (such as chlorine) will provide the required public health protection against waterborne diseases. However, if the primary use of ozone is for protozoa inactivation, a redundant ozone system becomes essential.

5.5.4 Maintenance Issues

In an ozonation system it is important to make sure that the ozone generator is working properly and is able to apply the ozone dosage required for effective disinfection. The variations in *CT* requirements due to fluctuations in water quality, ozone demand, pH and temperature should be determined accurately for the successful operation of the plant. Systems should develop standard operating procedures for addressing these issues. Systems should also ensure that a secondary disinfectant is applied to the finished water before it enters the distribution system so that it can maintain the necessary residual protection for the water.

In general ozone processes require a higher degree of operator skill and training. The ability to obtain qualified operators must be evaluated during the selection of the process. The production of ozone is also an energy intensive process requiring substantial electrical energy. Use of ozone may result in increases in organics content of the treated water. Hence, biologically active filtration may be necessary to stabilize the treated waters (GLUMRB 2003).

5.5.5 Monitoring Requirements

Ozone concentrations in water are generally monitored continuously using an aqueous ozone residual monitor, and confirmed periodically by hourly monitoring (Table 5.5.3) of ozone residual using the batch indigo method (APHA 2000). For hourly monitoring, determinations of residual concentrations of ozone are required but determinations of contact times are not essential. Periodic determinations of contact times are recommended, especially when there is a sudden change in water quality due to seasonal variations.

In order to control and monitor ozone levels in a contactor, and ensure *CT* values are met, each compartment of the contactor in which *CT* credit is to be taken should be equipped with sampling ports or probes for ozone analyzers. The residual levels of ozone should be measured

at a point representative of the lowest concentration expected in the compartment. If not, a minimum of two analysis points should be employed (IOA 1990).

All ozone systems for disinfection or oxidation must monitor their system for DBPs such as bromate. The monitoring requirements for bromate are provided in Table 5.5.3. The monitoring requirements for bromate can be reduced from monthly to quarterly if the system can demonstrate that the average source water bromide concentration is less than 0.05 mg/L based upon representative monthly bromide measurements for one year. Systems can remain on the reduced monitoring schedule until the running annual average source water bromide concentration, computed quarterly, is equal to or greater than 0.05 mg/L based upon representative monthly measurements (USEPA 2003a.).

Table 5.5.3: Monitoring Requirements for Ozone and Bromide

Location of monitoring in Plant	Frequency of monitoring
Ozone	
Within the ozone contactor	Hourly
Bromide	
Distribution System Entry Point	Monthly

Source: USEPA 2003a

5.5.6   Testing Protocols

Ozone concentrations must be determined by the indigo colorimetric method described in the *Standard Methods for the Examination of Water and Wastewater*, 20th edition, American Public Health Association, 2000.

For compliance monitoring for bromate, systems must use the ion chromatography analytical method as specified in USEPA Method 300.1, Determination of Inorganic Anions in Drinking Water by Ion Chromatography, Revision 1.0 (USEPA, 1997).

5.5.7   Safety Considerations

Ozone is a corrosive and toxic gas, which must be prevented from leaking. According to the Occupational Safety and Health Administration (OSHA) Standards in the United States, exposure to airborne concentrations should not exceed 0.1 mg/L (by volume) averaged over an eight-hour work shift (USEPA 2003).

In order to prevent inadvertent exposure from leaking ozone, ozone generators should always be housed indoors. Installation of ozone monitoring equipment and alarm systems are also necessary. Ventilation should be provided to prevent excess temperature in the generator room, and to exhaust the room in the case of a leak. There should be sufficient space to remove the tubes from the generator shell and to service the generator power supplies when

needed. If the off-gas destruction unit is located inside the building, an ambient ozone detector should be provided in the enclosure. All rooms should be properly ventilated, heated, and cooled (USEPA 2003a).

5.6 ULTRAVIOLET LIGHT

Ultraviolet light (UV) inactivates organisms by absorption of the light, which causes alterations to molecular components essential to cell function. In the past, it was considered that while being excellent for the inactivation of bacteria and viruses, UV was not capable of inactivating protozoan cysts at doses economical for use in the potable water industry. It has now been shown that UV effectively inactivates protozoan cysts. Viruses are considered to be the most resistant pathogens against UV radiation.

UV electromagnetic energy is typically generated by the flow of electrons from an electrical source through ionized mercury vapour in a lamp. Several manufacturers have developed systems to align UV lamps in vessels or channels to provide UV light in the germicidal range for inactivation of microorganisms. The UV lamps are similar to household fluorescent lamps, except that fluorescent lamps are coated with phosphorous, which converts the UV light to visible light. Ballasts (i.e., transformers) that control the power to the UV lamps are either electronic or electromagnetic. Advances in UV technology have resulted in more efficient lamps and more reliable equipment, and therefore, the use of UV technology has increased dramatically, particularly in the municipal sector.

UV radiation is classed as electromagnetic waves with a wavelength of 40 to 400 nm. The germicidal UV light wavelengths range from 200 to 300 nm, with the optimum germicidal effect occurring at 253.7 nm (Figure 5.6.1). Low-pressure lamps emit maximum energy at 253.7 nm while medium pressure lamps emit energy over a broad band of wavelengths, from approximately 200 to 1320 nm.

The inactivation of microorganisms by UV is directly related to UV dose; this is calculated from the product of the intensity of the light, measured in mW/cm^2 and the exposure time, measured in seconds. The UV dose is basically similar to the *CT* concept used for other common disinfectants such as chlorine and ozone. The average UV dose is calculated as follows:

$$D = I \times t$$

where:

D = UV Dose, $mW\text{-}s/cm^2 \, (mJ/cm^2)$

I = Average intensity, mW/cm^2

t = Exposure time, seconds

The survival fraction is calculated as follows:

Survival Fraction = log N/N$_o$

where:

N   =   Microorganism concentration after inactivation

N$_o$ =   Microorganism concentration before inactivation
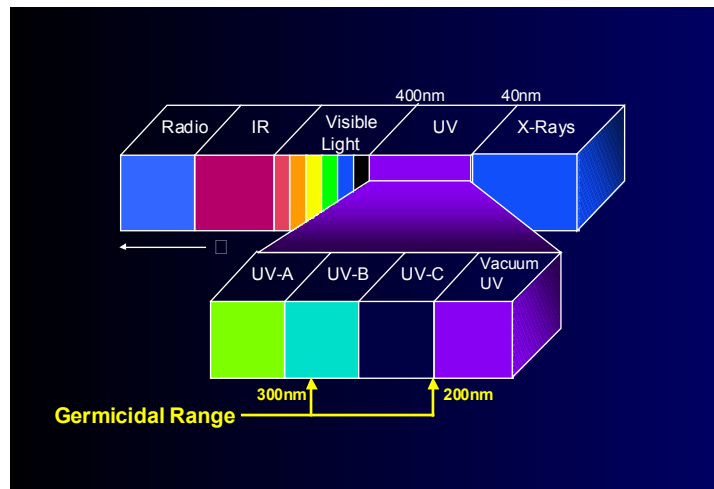
Figure 5.6.1: Spectrum of UV Light

The UV demand of the water is expressed as a percent transmittance. This is calculated from the absorbance of a sample at 254 nm in a 1-cm cell. The formula used is:

$$\% \,Transmittance = 100 \times 10^{-Absorbance}$$

High quality filtered water generally has an approximate UV transmittance of greater than 95 percent, while a good quality unfiltered water would generally have a UV transmittance of greater than 75 percent.

The above equations indicate that UV dose is directly proportional to exposure time and thus inversely proportional to system flowrate. UV intensity is a function of water UV transmittance and UV reactor geometry as well as lamp age and fouling. UV intensity can be estimated by mathematical modeling and confirmed by bioassays. Exposure time is estimated from the UV reactor-specific hydraulic characteristics and flow patterns. Mathematical models based on computational fluid dynamics (CFD) are good tools to define the residence time distribution for various flow elements.

UV disinfection is a physical process that uses photochemical energy to prevent cellular proteins and nucleic acids (i.e., DNA and RNA) from further replication. The germicidal effect of UV light is accomplished through the dimerization of pyrimidine nucleobases (e.g., thymine) on the DNA molecules to distort the normal helical structure and prevent cell replication. A cell that cannot replicate also cannot infect. Figure 5.6.2 shows a sketch of damage to the helical structure of DNA from UV radiation.
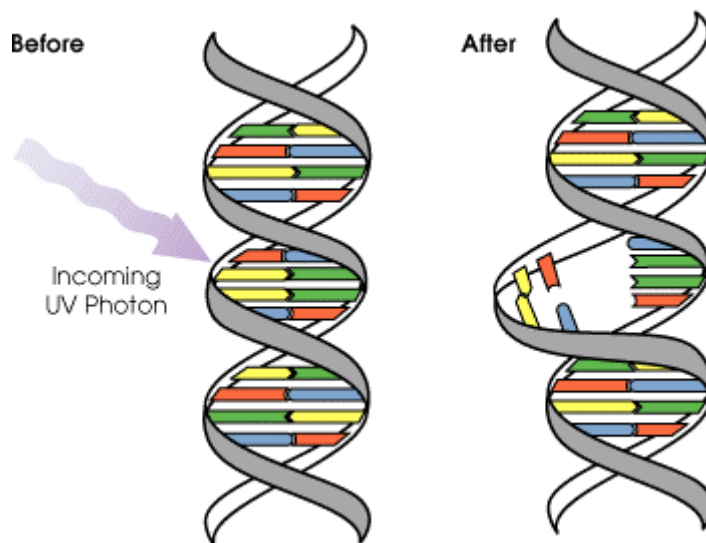
Figure 5.6.2: Damage to Helical Structure of DNA from UV Radiation

Some concern exists over self-repair mechanisms following UV disinfection, both dark and light. Photoreactivation has been observed in coliform indicator organisms and some pathogenic bacteria but other types of bacteria and viruses have been shown to be incapable of such repair. Previous work has been carried out by Shin et al. 1999, showing that *Cryptosporidium* and *Giardia* did not exhibit either dark or light repair mechanisms under their experimental conditions. However, they recommend further work is necessary to investigate other repair pathways.

5.6.1   Disinfection Effectiveness

A number of studies have shown the effectiveness of UV disinfection for the inactivation of several pathogenic microorganisms and they indicate that UV may be more effective than many chemical disinfectants for the inactivation of protozoa. Some of the results for the inactivation of *Cryptosporidium* and *Giardia* are summarized below:

- NSF/USEPA 1999: 3.9 log inactivation of *Cryptosporidium* at UV dose of 20 mJ/cm^2
- Finch and Belosevic 1999: 2.5 to 3.2 log *Cryptosporidium* inactivation at UV doses $\leq$20 mJ/cm^2
- Mofidi et al. 1999: 3 log *Cryptosporidium* inactivation at UV dose of 10 mJ/cm^2

- Shin et al. 1999: nearly 3.0 log *Cryptosporidium* inactivation using low-pressure UV dose $\leq$5 mJ/cm^2

- Clancy et al. 2000: 3.4 to >4.0 log *Cryptosporidium* inactivation using medium-pressure UV and 3.4 to 3.7 log *Cryptosporidium* inactivation using low-pressure UV at doses $\leq$9 mJ/cm^2

- Bolton et al. 1998: 3 log *Cryptosporidium* inactivation at UV doses $\leq$20 mJ/cm^2 and nearly 3 log *Giardia* inactivation at UV doses $\leq$25 mJ/cm^2

- Bukhari et al. 1999: 4.0 log *Cryptosporidium* inactivation at UV doses as low as 40 mJ/cm^2

- Soroushian et al. 2000: 4.0 log inactivation of *Giardia muris* with UV doses of 10 mJ/cm^2 or less. From concurrent experiments with MS-2 using the same low-pressure lamp equipment, UV doses of 40 mJ/cm^2 resulted in 1.8 to 2.2 logs of MS-2 inactivation.

- Craik et al. 2001: 3.0 log inactivation of *Cryptosporidium* oocysts at UV doses greater than approximately 25 mJ/cm^2 for both medium-pressure and conventional low-pressure lamps.

A summary of UV dosages required for 1.0 log and 3.0 log inactivation of various pathogens is provided in Table 5.6.1. The data on UV disinfection of bacterial pathogens indicate that 3 log inactivation of most organisms can be achieved with UV doses of 10 to 20 mJ/cm^2. Of the enteric indicator and pathogenic bacteria, *Klebsiella terrigena* and *Salmonella* are the most resistant to UV disinfection. However, both bacterial organisms are significantly easier to inactivate with UV light than viruses.

Table 5.6.1: UV Dose Required for Inactivation of Selected Waterborne Bacteria and Viruses

Microorganism	Ultraviolet Dose (mJ/cm^2) Required for:	
	1 log Inactivation	3 log Inactivation
Waterborne Bacteria		
Campylobacter jejuni	1.1	1.8 to 3.8
Escherichia coli	1.3 to 3.0	3.0 to 7.0
Klebsiella terrigena	3.9	9.1
Legionella pneumophila	0.92 to 2.5	2.8 to 7.4
Salmonella typhi	2.1 to 2.5	6.6 to 7.0
Shigella dysenteriae	0.89 to 2.2	2.1
Vibrio cholerae	0.65 to 3.4	2.2 to 2.9
Yersinia enterocolitica	1.1	2.7 to 3.7
Waterborne Enteric Viruses, Bacteria Spores, and Coliphage		
Adenovirus strain	23.6 to 30.0	80 to 90
Coxsackie virus	11.9 to 15.6	25 to 46.8
Echovirus type	10.8 to 12.1	32.5 to 36.4

Microorganism	Ultraviolet Dose (mJ/cm^2) Required for:	
	1 log Inactivation	3 log Inactivation
Hepatitis A Virus	3.7 to 7.3	15 to 21.9
Poliovirus Type	5.0 to 11.0	23.1 to 33
Poliovirus Type	10.3 to 12.0	30.9 to 36.1
Reovirus	15.4	45 to 46.3
Rotavirus	8.0 to 9.9	25 to 30
Bacillus subtilis spores	14.2	39.9
Coliphage MS-2	18.6	55 to 65

Source: Roessler and Severn 1996

Note: In developing the above results, the chemical and physical conditions of water quality generally were optimized for UV disinfection (i.e., low absorption, low turbidity, and filtration to minimize aggregation).

As shown in Table 5.6.1, the pathogenic viruses that can cause waterborne outbreaks are more resistant than other microorganisms. For example, the required dose for 3.0 log inactivation of viruses would range from 22 to 47 mJ/cm^2 for poliovirus, reovirus, rotavirus, Coxsackie virus, hepatitis A, and *Bacillus subtilus* spores. It should be noted that Coliphage MS-2, which requires a UV dose of 55 to 65 mJ/cm^2 for 3.0 log inactivation, is generally regarded as the most resistant organism to UV light.

5.6.2   Design Criteria

The USEPA has developed tables (USEPA 2003b) that designate the UV doses required to achieve credit for up to 3 log inactivation of *Giardia* and *Cryptosporidium* and up to 4 log inactivation of viruses. UV disinfection is an important technology for compliance with the upcoming Stage 2 D/DBP rules in the USA. UV dose tables play a role similar to the *CT* tables presented in the SWTR for chemical disinfectants (e.g. chlorine, ozone). The UV dose requirements determined by the USEPA for inactivation of *Cryptosporidium*, *Giardia*, and viruses are shown in Table 5.6.2.

Table 5.6.2: UV Dose (mJ/cm^2) Requirements (No Safety Factor) Used During Validation Testing

	Log Inactivation							
	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0
Cryptosporidium	1.6	2.5	3.9	5.8	8.5	12	-	-
Giardia	1.5	2.1	3.0	5.2	7.7	11	-	-
Virus	39	58	79	100	121	143	163	186

Source: USEPA 2003b

Table 5.6.3: UV Dose (mJ/cm^2) Requirements (With Safety Factor) Based on Validation Testing

| | Log Inactivation | | | | | | | |
	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0
Cryptosporidium	7.7	12	17	24	32	42	-	-
Giardia	7.5	11	15	23	30	40	-	-
Virus	63	94	128	161	195	231	263	300

Source: USEPA 2003b

It should be noted that the UV dose requirements stated in Table 5.6.2 do not take into account some very important design parameters such as water quality, lamp fouling/aging factor, flowrate, and power quality which can significantly affect the sizing of the UV reactors and the associated support facilities. Hence, it is important to determine the appropriate design values for these parameters. If the design parameters are not chosen conservatively enough, the UV reactors may be operating at a dose significantly less than the requirement (USEPA 2003b). The use of an appropriate safety factor is also highly prudent from a public health perspective. The UV dose requirements with safety factor determined by the USEPA for inactivation of *Cryptosporidium*, *Giardia*, and viruses are shown in Table 5.6.3.

The design parameters influencing the UV dose requirements are discussed below (USEPA 2003b):

Water Quality: The UV absorbance (A_{254}) of water at 254 nm directly influences UV dose delivery. The A_{254} data should be evaluated to select a A_{254} design value. The design A_{254}, specified UV dose and flowrate are used by the manufacturers to determine the appropriate UV reactor. Overly conservative design A_{254} values (or low UV transmissivity) can result in over-design and increased capital costs. Conversely, inappropriately low design A_{254} values can result in UV reactor operation to be out of compliance. Other water quality parameters such as turbidity, suspended solids, colour, etc., are also important. The maximum suggested limits for these parameters are indicated in Table 5.2.2.

Lamp Fouling: UV lamps are often subjected to fouling due to the influence of certain water quality characteristics. The rate of fouling depends on hardness, alkalinity, lamp temperature, pH, and certain inorganic constituents such as iron and calcium. These water quality parameters should be monitored prior to design unless adequate water quality data are available. It is important to provide these data to the UV manufacturer to assist them in a qualitative assessment of the fouling potential for their UV reactors and to assist the designer in determining what cleaning system should be specified.

Lamp Aging: Lamp output decreases over time due to physical aging. A reduction in lamp output results in a reduction in applied UV dose. The rate at which lamp output will decrease

is a function of the lamp characteristics, lamp hours in operation, number of on/off cycles, and power applied per lamp length. The effects of these parameters should be incorporated into UV reactor design by specifying a lamp fouling/aging factor, which is applied on the UV dose. This includes the effects of both sleeve fouling and lamp aging. The lamp fouling/aging factor is generally site-specific and is based on an assessment of fouling and lamp aging information. The lamp aging characteristics can be obtained from the UV manufacturer and should be certified by an independent third party.

Impact of Upstream Treatment Processes: Unit processes upstream of UV reactors can have a significant impact on UV reactor performance. The three potential ways that upstream processes may affect UV performance are: (1) increase UVT due to organics removal or the oxidizing of organics, (2) decrease UVT due to absorption of UV light by certain chemicals, and (3) effect on the lamp sleeve fouling rate. The use of filtration process upstream of the disinfection facility is recommended for better UV disinfection performance.

Flowrate: Flowrate also determines the necessary size and number of UV reactors. The design criteria should identify the average, maximum, and minimum flowrates that the UV reactors will experience.

Power: The electrical system and power supply are very critical to UV installation planning and design. The design of the electrical system needs to meet the requirements or recommendations for operating within validated conditions. To minimize the potential for off-specification operation, water systems should evaluate the reliability and quality of their power supply.

5.6.3   Types of UV Systems

There are presently several manufacturers of UV disinfection equipment with a large number of lamp configurations, types, and intensities. Research is continuing into new types of UV systems, such as pulsed output lamps, which are not yet feasible options for full-scale application in the municipal water treatment market. A summary of the characteristics of various types of UV lamp technologies currently being offered to the municipal market is provided in Table 5.6.4.

Mercury vapour lamps are the source of UV light for all systems, except for the pulsed UV system. The lamps are operated at either 10^{-3} to 10^{-2} torr (low-pressure lamps) or 10^{2} to 10^{4} torr (medium-pressure lamps). These two ranges give the highest conversion of electrical energy to UV light. Low-pressure mercury lamps are more efficient in converting electricity to germicidal UV light, but the total UV output is much weaker than from a medium-pressure lamp. The LPHI mercury lamps have design features to maintain mercury pressure at an optimum level under high discharge currents. A new generation of medium-pressure lamps

offers more concentrated outputs around specific wavelengths (e.g. "multiwave" lamps by Aquionics).

Table 5.6.4: General Characteristics of UV Disinfection Lamp Technologies

	Low-Pressure, Low-Intensity (LPLI)	Low-Pressure, High-Intensity (LPHI)	Medium-Pressure, High-Intensity (MPHI)
Mercury Vapour Pressure, torr	10^{-3} to 10^{-2} Optimal at 0.007	10^{-3} to 10^{-2} Optimal at 0.007	10^2 to 10^4
Operating Temperature, °C	40	60 to 250	600 to 900
UV Light Spectrum	Monochromatic (near 254 nm)	Monochromatic (near 254 nm)	Polychromatic (200 to 1320 nm)
Electrical Input, W/cm of lamp length	0.5	1.5-10	50-150
Germicidal UV Output, W/cm of lamp length	0.2	0.5-3.5	5-30
Electrical to Germicidal UV Conversion Efficiency, %	35-38	30-35	10-20
Power Consumption, W	70	170 to 1,600	2,000 to 20,000
Arc Length, cm	45-150	45-150	120
Lamp Output	Constant	Adjustable	Adjustable
Relative Number of Lamps Required for a Given Dose	High	Intermediate	Low
Rated Lifetime, hrs	8,000-10,000	8,000-10,000	3,000-5,000
Cleaning	Manual	Automatic	Automatic

nm = nanometers

There are significant differences in power input, intensity output, lamp arc length, power supply requirements, and reactor configuration among these systems. The LPHI systems emit monochromatically and the majority of emissions are produced at the germicidal wavelength of 254 nm. For the MPHI UV systems, the UV light spectrum that is emitted from the lamps is polychromatic. The germicidal effectiveness varies for each wavelength in the range of 200 to 300 nm, so the estimation of the germicidal efficiency requires a calculation that accounts for the output and germicidal effectiveness at each wavelength.

5.6.4   Operational Requirements

The principal operational requirements of UV reactors are to operate within validated limits. All water systems should demonstrate that at least 95 percent of the water delivered to the consumers each month is operated within validated limits.

The water quality needs to be analyzed by a certified laboratory before UV application. If required, pre-treatment of the water is necessary if certain water quality parameters exceeds certain limits.

Raw water quality should be evaluated and the necessary pre-treatment equipment should be selected based on the water quality changes. The variation in water quality due to seasonal changes should also be considered in the water quality evaluation (GLUMRB 2003).

Other important operating requirements for UV application are as follows (GLUMRB 2003):

- UV radiation should be applied at the correct wavelength(s)
- The manufacturer's maximum rated flow and pressure should not be exceeded during the design and installation of the UV reactor
- The UV device shall be fitted with a light sensor to safely verify that UV light is being delivered into the reactor
- The UV light assembly should not be in direct contact with the influent water
- Pre-screening should be done to avoid lamp damage
- UV reactors should be kept free of air by using air release valves to prevent lamp damage
- Formation of negative pressures or surge effects within the UV reactor should also be prevented by using air/vacuum valves to avoid damage to the lamp sleeve and UV lamps
- The UV reactors must remain flooded at all times during operation
- All materials used in construction or coating the reactors and in contact with water shall be in compliance with NSF International Standard 61 Drinking Water System Components-Health Effects and other applicable codes (NWRI/AWWARF 2003)
- Any chemicals used to clean the quartz sleeves should be certified and listed in accordance with NSF Standard 60 Drinking Water Treatment Chemicals-Health Effects (NWRI/AWWARF 2003)
- An automatic shutdown valve should be installed in the water supply line ahead of the UV treatment system that will be activated whenever the UV lamp loses power below a certain threshold value.

5.6.5   Maintenance Issues

Maintenance of UV reactors is important to ensure that the disinfection requirements are met. Some of the general guidelines for UV reactor maintenance are as follows (USEPA 2003b):

UV Lamp Characteristics: In general UV lamp output decreases with time and hence lamps need to be replaced periodically. The frequency of lamp replacement should be determined using the lamp operating hours and the UV intensity reduction as measured by the UV intensity sensor. The lamps should be replaced with identical lamps used during reactor validation. Some of the key characteristics of the lamps, which should be identical, are arc length, lamp envelope material and dimensions, amount of mercury, and spectral output.

UV Intensity Sensors: Efficient sensor calibration, rotation and placement are key factors for the validation of UV intensity. In general there are two types of sensors, which are frequently used: duty sensors, which continuously monitor UV intensity and reference sensors, which are

used to assess the duty sensor performance. Hence, the reference sensor and duty sensor performance should exactly match each other so that a valid comparison can be completed. The reference sensors should be calibrated at least once a week. Water systems may choose to have multiple reference sensors in order to determine whether any one of them is out of calibration.

Lamp Sleeves: Deterioration of lamp sleeves causes loss of UV transmittance. Lamp sleeves should be handled in accordance with manufacturer recommendations. In general they should be replaced every 3 to 5 years depending upon the level of damage or the level of fouling. However, the frequency of replacement could be increased or decreased depending upon the operational experience.

Fouling: Fouling on UV lamps is depended upon a number of factors such as water quality, lamp type, and cleaning regime. The best way of avoiding fouling is by cleaning frequently. The cleaning system must deal effectively with site-specific water-quality effects (e.g. precipitation and fouling due to iron, calcium, aluminium, manganese and other organic and inorganic constituents) (NWRI/AWWARF 2003). An automatic mechanical cleaning system is recommended for UV lamps instead of manual or chemical cleaning.

UV Transmittance Monitor Calibration: The online UV transmittance should be compared to bench-top spectrophotometer readings every week. The frequency of comparison may be increased or decreased based on previous experiences over the last year.

UV Reactor Temperature: If the temperature of the water exceeds a certain threshold value as specified by the manufacturer, UV lamps can break. Hence, the water temperature should always be monitored. If the temperature exceeds the limit, the UV reactor should be shut down.

Alarms: Alarms are required for the operation of a UV disinfection system. Alarms are essential to indicate lamp failures, low UV intensity, low UV dose, high turbidity, high or low water level, and low UV transmittance. The set point of these alarms should allow for an adequate response time based on the importance of the alarm and subsequent consequences.

Power Control: Power usage should be controlled in order to operate the reactor efficiently. Operational adjustments such as changes in flow, UV intensity, UV transmittance, and other factors can influence the power consumption significantly. Hence power consumption should be monitored and adjusted in accordance with the operational changes.

5.6.6   Monitoring Requirements

The major factor affecting the performance of UV disinfection systems is influent water quality. Particles, turbidity, and suspended solids can shield pathogens from UV light or

scatter UV light, preventing it from reaching the target microorganism and thus reducing its effectiveness as a disinfectant.

Some organic compounds and inorganic compounds (such as iron and permanganate) can reduce UV transmittance by absorbing UV energy, requiring higher levels of UV to achieve the same dose. Calcium carbonate (hardness) is one of the rare compounds with decreasing solubility at higher temperature. Hence, at elevated temperatures calcium carbonate may be precipitated which may reduce the UV transmittance. These above factors will generally be minimized when the UV system is preceded by a clarification and filtration stage. However, if used on filtered surface water, the contribution of these factors is not well understood. Temperature can be of concern with low-pressure systems, where the lamp temperature must be kept above 5°C. Sleeve elevated temperature can promote scaling. Clumping of microorganisms and fouling of lamps or sleeves may also decrease the inactivation of microorganisms.

For regular full-scale operation of the UV system, several criteria will be continuously monitored to verify performance of the UV disinfection system. These performance criteria include:

- Flowrate
- UV transmittance
- Calculated UV dose
- Power consumption
- UV intensity

In addition, there may be other criteria that are identified for regular performance monitoring. The flowrate through each reactor is monitored using magnetic flowmeters mounted on the inlet to each reactor. Flow control valves are installed downstream of each reactor for use in maintaining the flowrate through each reactor. The flow control valves ensure that the flowrate through each reactor remains within the range of values demonstrated as part of the validation testing.

UV transmittance is continuously monitored using an on-line process analyzer. The analyzer will require regular calibration with a bench-top unit to ensure accuracy. The continuous UV transmittance readings alert the operators if UV transmittance decreases to less than the specified value.

The system's programmable logic controller (PLC) continuously calculates the theoretical UV dose applied in each reactor based on the age of the lamps within each reactor, the flowrate through the reactor, and the measured value of UV transmittance. The system records the dose, and is programmed to maintain dose above an operator-entered set point. For small drinking water systems this may not be feasible. The only other option for them is to monitor

the power consumption. The system should be designed with the capability to monitor power consumption by each reactor. If possible the power consumption should be tied to alarms to indicate excessive power consumption as well as power consumption below anticipated values for the given conditions.

5.6.7 Validation Testing

The basic purpose of validation is to provide a level of confidence that a UV reactor can provide a certain level of inactivation required for the application. The uncertainty experienced should be addressed with a safety factor. The process of validation is particularly important for UV disinfection because its successful operation is highly dependent upon the site-specific conditions and also on equipment performance.

The experimental testing procedure of the validation process is referred to as "biodosimetry". It basically consists of a UV reactor that measures log inactivation of a challenge microorganism under various flowrate, UV transmittance, and lamp power combinations. The details of the validation testing procedure are explained in the *UV Disinfection Guidance Manual* (USEPA 2003b) published by the USEPA. The validation of UV reactors can be done in the following ways:

1) *Challenge Microorganism Preparation* – Challenge microorganisms should be prepared in accordance with established methods. Information regarding the source of the host, media descriptions, and preparation steps must be documented. The two most frequently used challenge microorganisms are MS2 phage and *B. subtilis* spores. The same batch of organisms should be used in the next two steps of the validation procedure in order to eliminate the batch-to-batch variation of the microorganisms' resistance to UV light.

2) *Collimated Beam Testing* – The collimated beam test is a standard test used to develop the dose-response curve for the challenge microorganism. It typically consists of a collimated beam apparatus, which is an enclosed low-pressure UV lamp and a tube. The challenge microorganism is placed in a petri-dish and is exposed to UV light for a certain period of time. The UV dose is then calculated using the intensity of the incident UV light, UV absorbance and exposure time.

3) *Biodosimetry of Full-Scale Reactors* – Collimated beam tests are batch operations, which may not be representative of the continuous operation experienced in actual plants. Hence, biodosimetry test is conducted to determine the inactivation of the challenge microorganism under actual conditions.

Based on this validation procedure the actual dose of UV is determined in order to meet the objective of microorganism inactivation (USEPA 2003b).

For small drinking water systems, validation testing becomes unreasonable due to cost considerations. Typically, when evaluating UV technology a small drinking water system should consider measuring the UV transmittance and the flowrate at a minimum. Typically, a transmittance value of 85% or higher is recommended for the use of UV to disinfect water for small drinking water systems. Under no circumstances should UV be used below 75%

transmittance. Since every UV system is designed to treat a maximum flow rate based on a specific transmittance value, it is important to install a system of adequate size to accompany maximum flow rates while achieving the required dose. In general, in order to avoid the expenses of conducting validation testing, small drinking water systems should use NSF certified UV equipment and a conservative UV design dose as a precaution. Small drinking water systems should also choose UV systems, which require minimal operator intervention in terms of routine annual maintenance such as changing out the lamps and quartz sleeves. UV systems that are designed with instrumentation and other features such as quartz sleeve wiper mechanisms, lamp out alarms, heat sensors and UV intensity monitors are preferable in such situations.

5.6.8 Safety Considerations

The Office of Safety and Health Administration (OSHA) in the United States identified the following issues with regard to safety in the workplace for UV reactor operation in water treatment plants (USEPA 2003b):

- UV light exposure causing eye injury or skin damage
- Electrical shock
- Burns from hot lamps or equipment
- Abrasions or cuts from broken lamps
- Potential exposure to mercury from broken lamps

Precautions and safety measures should be adopted to avoid these potential hazards during UV operation.

5.7 CHLORINE DIOXIDE

Chlorine dioxide must be generated on-site by the reaction of sodium chlorite ($NaClO_2$) and gaseous chlorine or hypochlorous acid ($HOCl$) or hydrochloric acid (HCl). The reactions are as follows:

$$2NaClO_2 + Cl_{2(g)} = 2ClO_{2(g)} + 2NaCl$$

$$2NaClO_2 + HOCl = 2ClO_{2(g)} + NaCl + NaOH$$

$$5NaClO_2 + 4HCl = 4ClO_{2(g)} + 5NaCl + 2H_2O$$
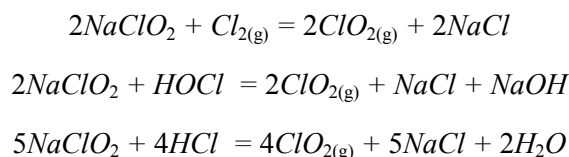
Chlorine dioxide received significant attention during the late 20th century due to the substantial research conducted by the scientific community on protozoan parasites such as *Cryptosporidium*. In research it was shown conclusively that chlorine dioxide is an effective disinfectant for controlling these types of encysted parasites. At the same time new methods of chlorine dioxide generation became available (White 1999).

5.7.1 Disinfection Effectiveness

Chlorine dioxide is a strong oxidant and it is very effective in the inactivation of pathogens. Its oxidizing ability is lower than ozone but much stronger than chlorine and chloramines. The early investigations with chlorine dioxide concluded that the bacterial efficiency of chlorine dioxide towards *E. coli*, *Salmonella typhosa*, and *Salmonella paratyphi* was as great as or greater than that of chlorine (White 1999). Investigations (White 1999) also revealed that chlorine dioxide is more effective than either ozone or chlorine against certain viruses. Against encysted parasites such as *Giardia* and *Cryptosporidium* oocysts it has been found that chlorine dioxide can achieve necessary levels of inactivation at practical dosage levels (Finch et al. 1995). Due to its strong biocidal ability, chlorine dioxide is very effective for slime control. Chlorine dioxide is also very effective for controlling zebra mussels.

Chlorine dioxide disinfection kinetics are dependent upon pH, temperature, and suspended matter. The effect of pH is less dominant compared to chlorine. Earlier studies (Le Chevallier et al. 1997) found that the inactivation rate of *Giardia* increases at higher pH. In others it was found to have no effect (Ridenour and Ingols 1947). Similar to chlorine the disinfection effectiveness of chlorine dioxide is highly dependent upon temperature. In general, the effectiveness decreases with decreasing temperature. Suspended solids in water promote pathogen aggregation and interfere with the disinfection kinetics of chlorine dioxide (USEPA 1999).

Chlorine dioxide does not form THMs when it is applied to water containing organic compounds, thus eliminating the need for THM control. However, the reactions of chlorine dioxide form chlorite (ClO_2^-) and chlorate (ClO_3^-) ions, which can cause adverse health effects. The USEPA recommends that chlorite concentration in the distribution system must be less than 1.0 mg/L. Chlorites can be removed by applying either granular activated carbon (GAC) or powdered activated carbon (PAC).

5.7.2 Design Criteria

Chlorine dioxide is a strong disinfectant and can effectively inactivate bacteria, viruses and protozoa. *CT* values required for the disinfection of virus and protozoan cysts such as *Giardia* were determined and documented in earlier reports (AWWA 1991, LeChaevallier et al. 1996) as shown in Figures 5.7.1 and 5.7.2, and Table 5.7.1. The *CT* requirements are highest for protozoan oocyst *Cryptosporidium*. The shift from conventional disinfection to chlorine dioxide should meet the requirements for inactivating *Cryptosporidium* because it is the most resistant among the waterborne pathogens. The *CT* values required for *Cryptosporidium* inactivation are shown in Table 5.7.2.
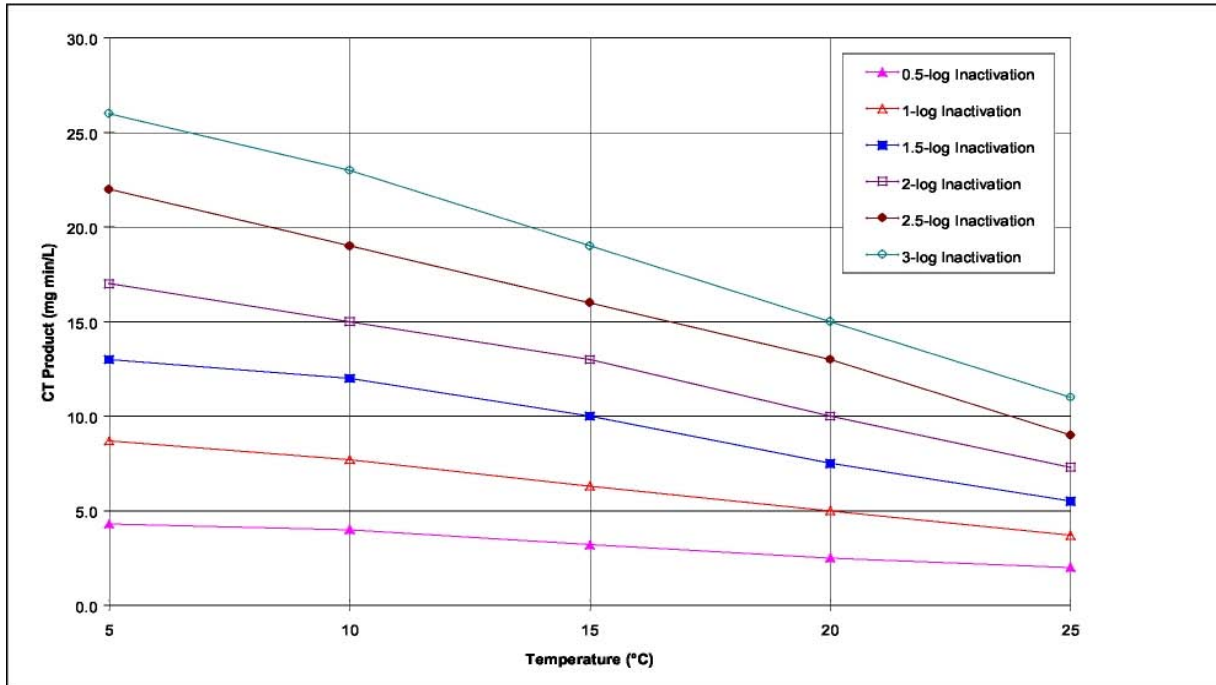
Source: AWWA 1999

Figure 5.7.1: *CT* Values for Inactivation of *Giardia* Cysts by Chlorine Dioxide
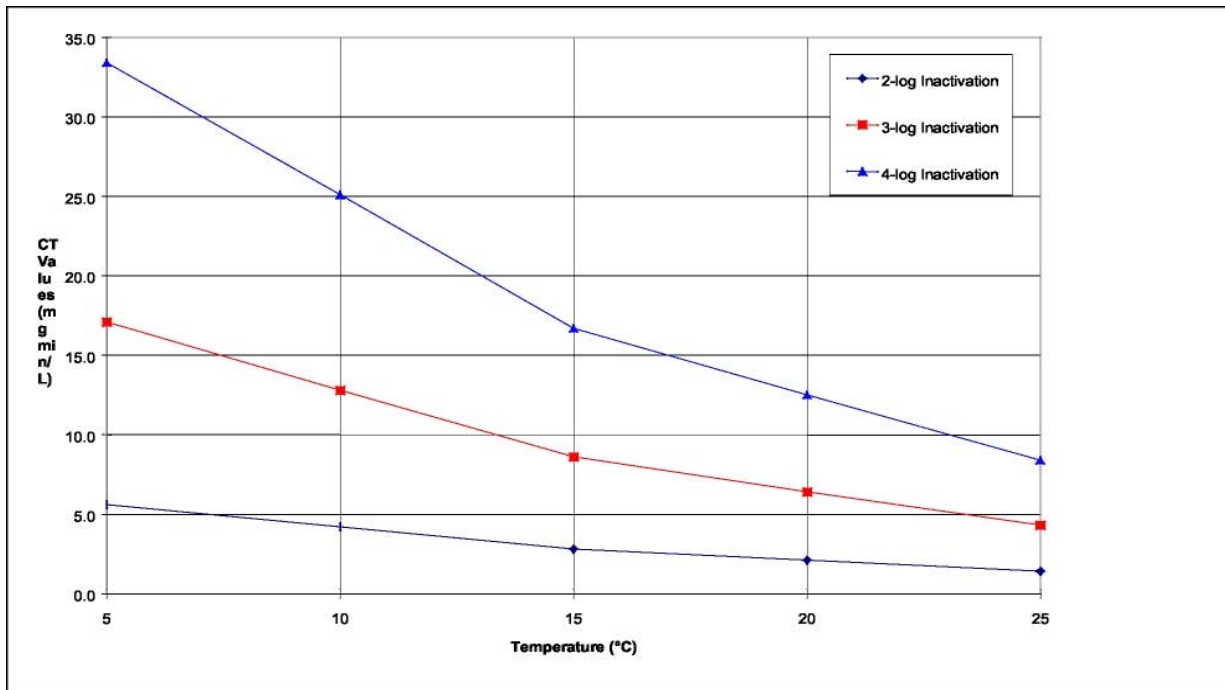
Source: USEPA 1999

Figure 5.7.2: *CT* Values for Inactivation of Viruses by Chlorine Dioxide

Table 5.7.1: *CT* Values (mg·min/L) for *Giardia* Cyst and Virus Inactivation Using Chlorine Dioxide at ≤ 1°C Between pH 6 to 9

Pathogens	Log Inactivation			
	1.0	2.0	3.0	4.0
Giardia Cyst	21	42	63	-
Virus	-	8.4	25.6	50.1

Source: MOE 2003

Table 5.7.2: *CT* Values (mg·min/L) for *Cryptosporidium* Inactivation Using Chlorine Dioxide

Log credit	Water Temperature, °C									
	≤ 0.5	1	2	3	5	7	10	15	20	25
0.5	319	305	279	256	214	180	138	89	58	38
1.0	637	610	558	511	429	360	277	179	116	75
1.5	956	915	838	767	643	539	415	268	174	113
2.0	1275	1220	1117	1023	858	719	553	357	232	150
2.5	1594	1525	1396	1278	1072	899	691	447	289	188
3.0	1912	1830	1675	1534	1286	1079	830	536	347	226

CT values between the indicated temperatures may be determined by interpolation
Source: USEPA 2003a

The inactivation kinetics of chlorine dioxide are dependent upon factors such as pH, temperature, and suspended solids. In general, pH has much less effect on pathogen inactivation with chlorine dioxide as compared to chlorine. More research is needed to further clarify the effect of pH on the inactivation kinetics of chlorine dioxide (USEPA 1999).

The *CT* requirement of *ClO₂* for the inactivation of *Cryptosporidium* is particularly sensitive at low temperatures. As evident from Table 5.7.1, as the temperature declines, chlorine dioxide becomes less effective as a disinfectant. Since the treatment achieved for chlorine dioxide addition is temperature dependent, systems need to consider the variation in water temperature to ensure they meet the *CT* level for the minimum treatment needed for compliance (USEPA 1999).

Suspended solids and pathogen aggregation can affect the inactivation kinetics significantly. Earlier studies (Chen et al. 1984; Brigano et al. 1978) have demonstrated that the dosage requirements of chlorine dioxide for virus and protozoan cyst inactivation can be several times higher due to the presence of suspended solids in water (USEPA 1999). The water quality characteristics of the water to be treated by chlorine dioxide should generally meet the standards mentioned earlier in Table 5.2.2.

5.7.3   Generation

There are several methods of generating chlorine dioxide the details of which are available elsewhere (Gates 1998). Brief descriptions of some of these processes are provided below (USEPA 1999).

The conventional generation of chlorine dioxide is done in two steps. First, chlorine gas is reacted with water to form hypochlorous acid and hydrochloric acid. These acids are then reacted with sodium chlorite to form chlorine dioxide.

Acid-Chlorite solution - Chlorine dioxide can be generated in direct-acidification generators by acidification of sodium chlorite solution.

Aqueous Chlorine-Chlorite solution - Reaction of dissolved sodium chlorite with hydrochloric acid and hypochlorous acid can generate chlorine dioxide (Figure 5.7.3).
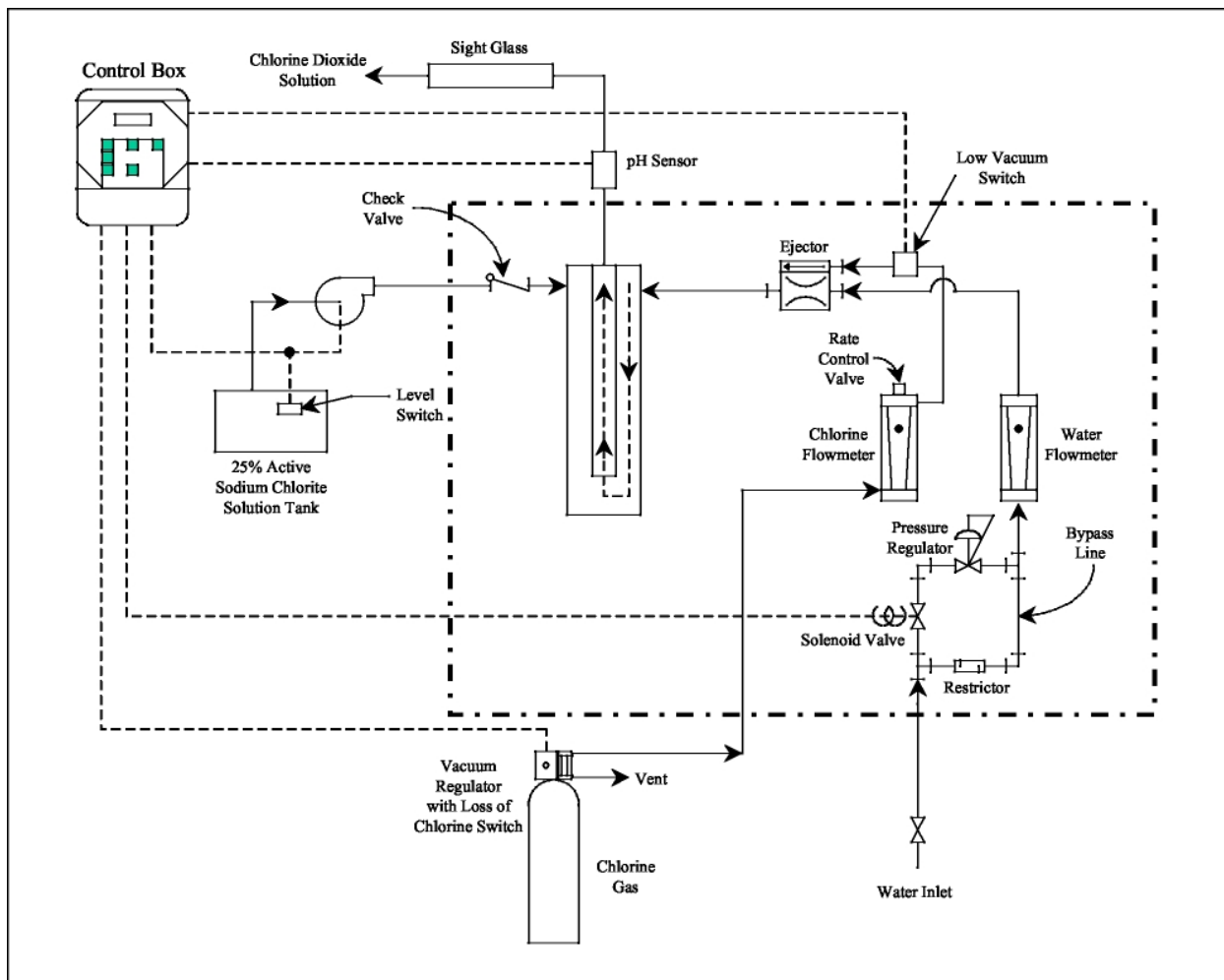
Source: USEPA 1999

Figure 5.7.3: Conventional Chlorine Dioxide Generation When Using Chlorine-Chlorite Method*

Recycled Aqueous Chlorine – In this process chlorine gas is injected into a continuously circulating water loop (Figure 5.7.4). This eliminates the need for a great excess of chlorine to be fed as the chlorine dissolves in water and maintains a low pH in the feed water. This low pH condition results in high yields of chlorine dioxide (Thompson 1989). However, this type of chlorine dioxide generator is difficult to operate due to start-up and control of chemical feed rates.

Gaseous Chlorine-Chlorite Solution – In this process sodium chlorite solution is vapourized and reacted under vacuum with gaseous chlorine.
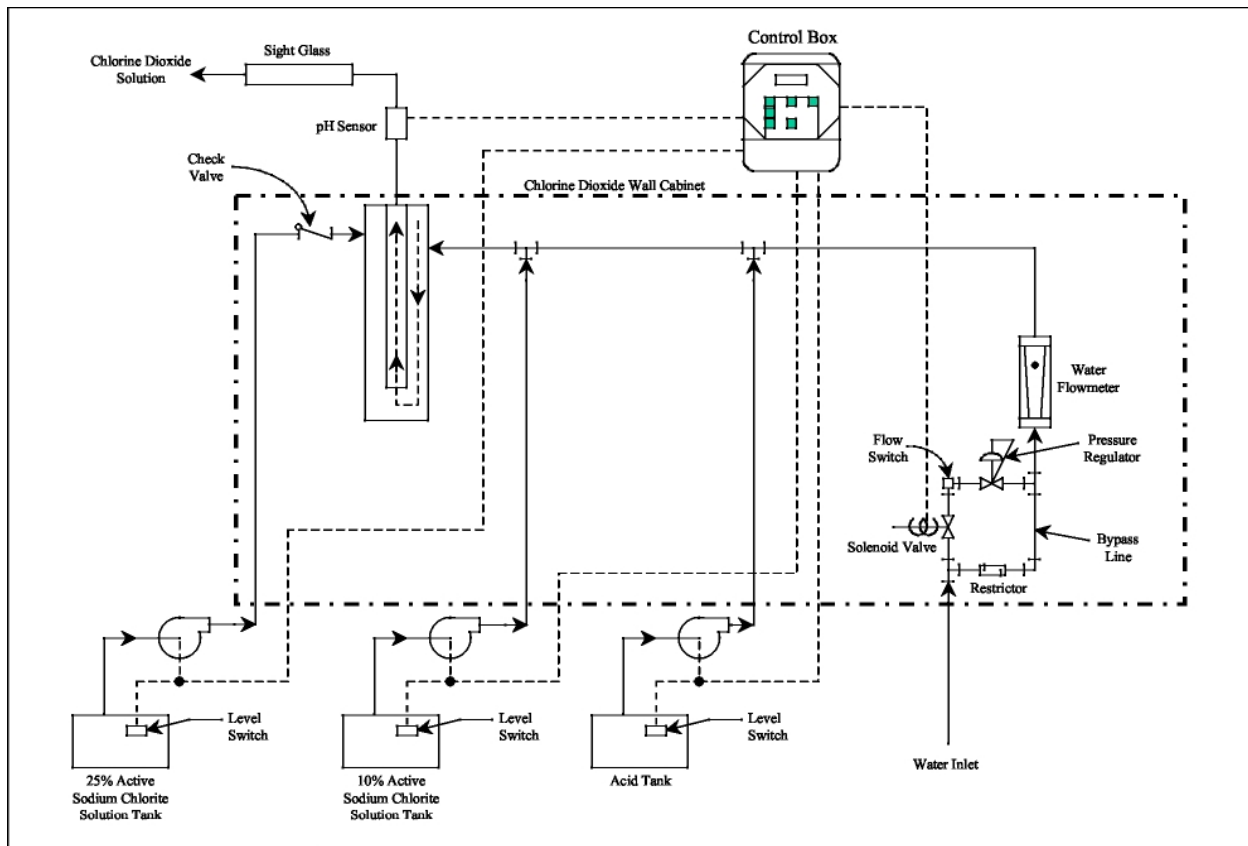
Source: Demers and Renner, 1992.

Figure 5.7.4: Chlorine Dioxide Generation Using Recycled Aqueous Chlorine Method

The basic components of a chlorine dioxide generation system consist of the following (USEPA 1999):

- Chemicals (aqueous hypochlorite solution and sodium chlorite) storage and feed systems
- Chlorine storage and feed systems
- Chlorine dioxide generator

- Chlorine dioxide feed piping and dispersion equipment

The chemical storage and feed pumps are basically liquid systems that consist of storage tanks and solution feed pumps. Sodium chlorite should be stored properly as crystallization of sodium chlorite can occur as a result of low temperatures or higher concentrations. Crystallization can plug pipelines, valves, and other equipment. Hence, in Manitoba, outside storage of sodium chlorite is not recommended.

5.7.4   Maintenance Issues

The lowering of optimal concentrations of precursor reactants will increase chlorate levels in the chlorine dioxide generator. Therefore, if weak precursor feed stocks or high amounts of dilution water are added to the generator, chlorate will be more prevalent. Due to this reason generators most often use ~25 percent chlorite solutions and gaseous (or near-saturated aqueous) chlorine. Higher strength solutions of sodium chlorite (e.g., 37 percent) are more susceptible to crystallization or stratification at ambient temperatures as high as 25ºC (USEPA 1999).

During the handling and storage of sodium chlorite solutions, crystallization should not be allowed to occur as a result of lower temperatures and/or higher concentrations. Crystallization will plug pipelines, valves, and other equipment. Sodium chlorite solution should not be allowed to evaporate to a powder. If dried, this product becomes a fire hazard and can ignite in contact with combustible materials (USEPA 1999).

In sodium chlorite holding tanks stratification may occur and may influence the chlorine dioxide yield. If stratification occurs in the bulk tank, sodium chlorite changes from high density to low density as it is fed. The density will continue to change until the material is re-mixed (USEPA 1999). If stratification or crystallization occurs in bulk delivery trucks, the entire content should be warmed prior to delivery so that the sodium chlorite is re-mixed. Operators should be aware of the possibility of stratification and crystallization during delivery conditions (USEPA 1999).

5.7.5   Monitoring Requirements

When chlorine dioxide is used as a secondary disinfectant, the requirements for monitoring should reflect the entire distribution system. All systems using chlorine dioxide for disinfection should monitor both chlorine dioxide and DBP (chlorite) on a daily basis. The requirements for monitoring at different locations of the plant are shown in Table 5.7.3.

Table 5.7.3: Monitoring Requirements For Chlorine Dioxide and Chlorite

Location of monitoring in Plant	Frequency of monitoring
Chlorite	
Distribution System Entry Point	Daily
Distribution System: 1 at first customer 1 at the middle of distribution system 1 at maximum residence time	Monthly
Chlorine Dioxide	
Distribution System Entry Point	Daily

Source: USEPA 2003a

Assumption: Chlorine dioxide is used as a secondary disinfectant

For determining the location of monitoring at the maximum residence time, water quality modeling software such as *WaterCAD* is recommended. On each day when the permissible chlorite level is exceeded, additional samples should be taken at the same locations as identified in Table 5.7.2.

Chlorine dioxide monitoring in the distribution system may not be reduced under any circumstances. This is because chlorine dioxide decays quickly and fails to provide necessary residual concentrations in the finished water for a long time. Chlorine dioxide can only be used as a disinfectant where the distribution system is small and less complex. On each day following a routine sample monitoring result that exceeds the maximum permissible value, the system is required to take at least three additional samples in the distribution systems.

Chlorites are known to have adverse health effects and their presence in the distribution system is a source of concern. Hence, both small and large systems using chlorine dioxide, are required to monitor chlorites. For chlorite monitoring, water systems that use chlorine dioxide for disinfection are required to take daily samples at the entrance to the distribution system (USEPA 1999). For any daily sample that exceeds the chlorite MCL (maximum contaminant level) of 1.0 mg/L, the system must take additional samples in the distribution system the following day at the locations specified in Table 5.7.3. In addition, systems using chlorine dioxide must take a three-sample set each month in the distribution system similar to those three locations if the chlorite MCL is exceeded in the sample collected at the entrance to the distribution system (USEPA 1999). This monthly sampling requirement may be reduced to quarterly after one year of monitoring where: (1) no individual chlorite sample taken in the distribution system has exceeded the MCL and (2) the system has not been required to conduct follow-up monitoring as a result of a daily sample collected at the entrance to the distribution system. These systems can remain on an annual schedule until either the daily sample or any of the three individual quarterly samples exceed the MCL, at which time, the system must revert to monthly monitoring (USEPA 1999).

5.7.6 Testing Protocols

One of the difficulties experienced by water treatment plants that use chlorine dioxide is the complexity and sensitivity of the method of analysis. The two EPA approved procedures are Amperometric and DPD Titration methods. Both require highly skilled analysts, and can take upwards of 40-45 minutes per sample. For testing of chlorine dioxide and chlorite, all water systems must use the protocol described in *Standard Methods for the Examination of Water and Wastewater*, 20th edition, American Public Health Association, 2000. For small drinking water systems where easy access to laboratory facilities is not available, the use of Hach Powder Pillows and AccuVac® Ampoules for the measurement of chlorine dioxide may be acceptable. The method is equivalent to *Standard Methods, 20th edition., 4500 ClO_2 D*, and is USEPA accepted for reporting for drinking water analysis.

5.7.7 Safety Considerations

Chlorine dioxide has a significant vapour pressure, which increases as a function of dissolved chlorine dioxide and time. As such, concentrated aqueous solutions of chlorine dioxide should be handled with care. In general, vapour pressure of chlorine dioxide in excess of 75 to 80 mm Hg is considered dangerous and should be avoided. Sodium chlorite is a strong oxidizer and it can ignite when it dries in contact with combustibles. Sodium chlorite can also react with a number of chemicals such as acids and hypochlorites to cause the uncontrollable release of chlorine dioxide gas. Commercial sodium hypochlorites contain additives that reduce shock and heat sensitivity of this chemical and improve safety (White 1999).

SECTION 6.0
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APPENDIX A
CT TABLES AND FIGURES FOR DISINFECTANTS

Table A1: *CT* Values for Virus Inactivation by Free Chlorine

Temperature (ºC)	Log Inactivation					
	2		3		4	
	pH		pH		pH	
	6 to 9	10	6 to 9	10	6 to 9	10
0.5	6	45	9	66	12	90
5	4	30	6	44	8	60
10	3	22	4	33	6	45
15	2	15	3	22	4	30
20	1	11	2	16	3	22
25	1	7	1	11	2	15

Source: USEPA 1999

Source: USEPA 1999

Figure A1: *CT* **Values for Inactivation of *Giardia* Cysts by Free Chlorine at 10ºC (at Cl$_2$ dose of 3.0 mg/L)***
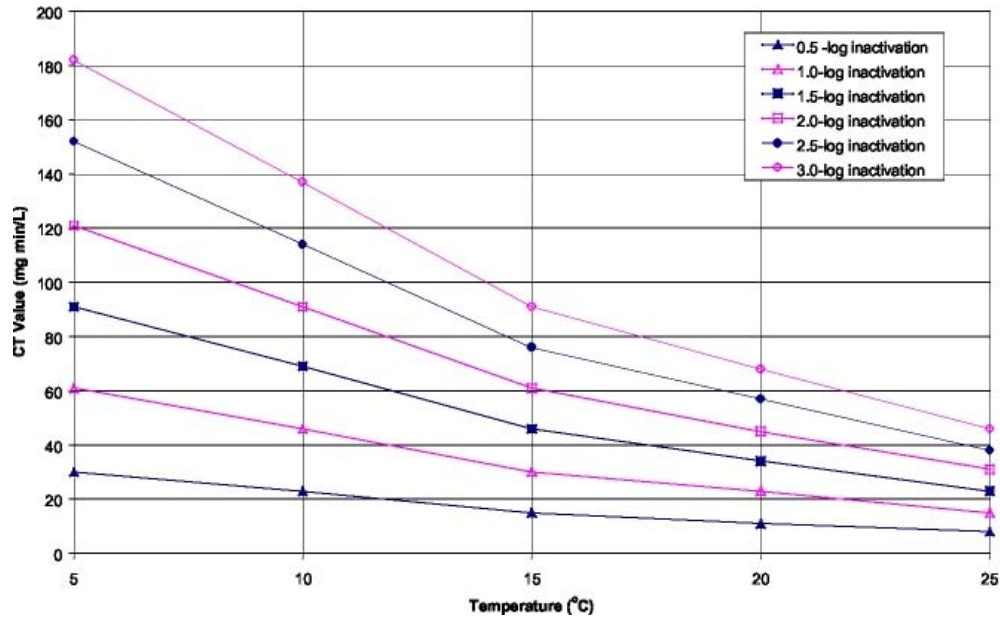
Source: USEPA 1999

Figure A2: *CT* **Values for Inactivation of *Giardia* Cysts by Free Chlorine at pH 7.0 (at *Cl*₂ dose of 3.0 mg/L)**

Table A.2: *CT* Values (mg·min/L) for Inactivation of *Giardia* Cysts by Free Chlorine at 0.5ºC or lower

pH	Log Inactivation					
	0.5	**1**	**1.5**	**2.0**	**2.5**	**3.0**
≤ 6	23-30	46-69	69-91	91-121	114-151	137-181
6.5	27-36	54-72	82-109	109-145	136-181	163-217
7.0	33-44	65-87	98-131	130-174	163-218	195-261
7.5	40-53	79-105	119-158	158-211	198-263	237-316
8.0	46-64	92-127	139-191	185-255	231-318	277-382
8.5	55-77	110-153	165-230	219-307	274-383	329-460
9.0	65-92	130-184	195-276	260-368	325-460	390-552

Source: MOE 2003

Table A3: *CT* Values for *Giardia* Cyst Inactivation Using Chloramines

Inactivation (log-units)	*CT* (mg·min/L)				
	5ºC	10ºC	15ºC	20ºC	25ºC
0.5	365	310	250	185	125
1.0	735	615	500	370	250
1.5	1,100	930	750	550	375
2.0	1,470	1,230	1,000	735	500
2.5	1,830	1,540	1,250	915	625
3.0	2,200	1,850	1,500	1,100	750

Source: USEPA, 1999.
Values shown in this table are based on a pH range between 6 and 9.

Table A4: *CT* Values (mg·min/L) for Virus Inactivation Using Chloramines

Inactivation (log-units)	*CT* (mg·min/L)				
	5ºC	10ºC	15ºC	20ºC	25ºC
2	857	653	428	321	214
3	1,423	1,067	712	534	356
4	1,988	1,491	994	746	497

Source: USEPA, 1999

Table A5: *CT* Values (mg·min/L) for *Giardia* Cyst and Virus Inactivation Using Chloramines at ≤ 1°C between pH 6 to 9

Pathogens	Log Inactivation			
	1.0	2.0	3.0	4.0
Giardia Cyst	1270	2535	3800	-
Virus	-	1243	2063	2883

Source: MOE 2003
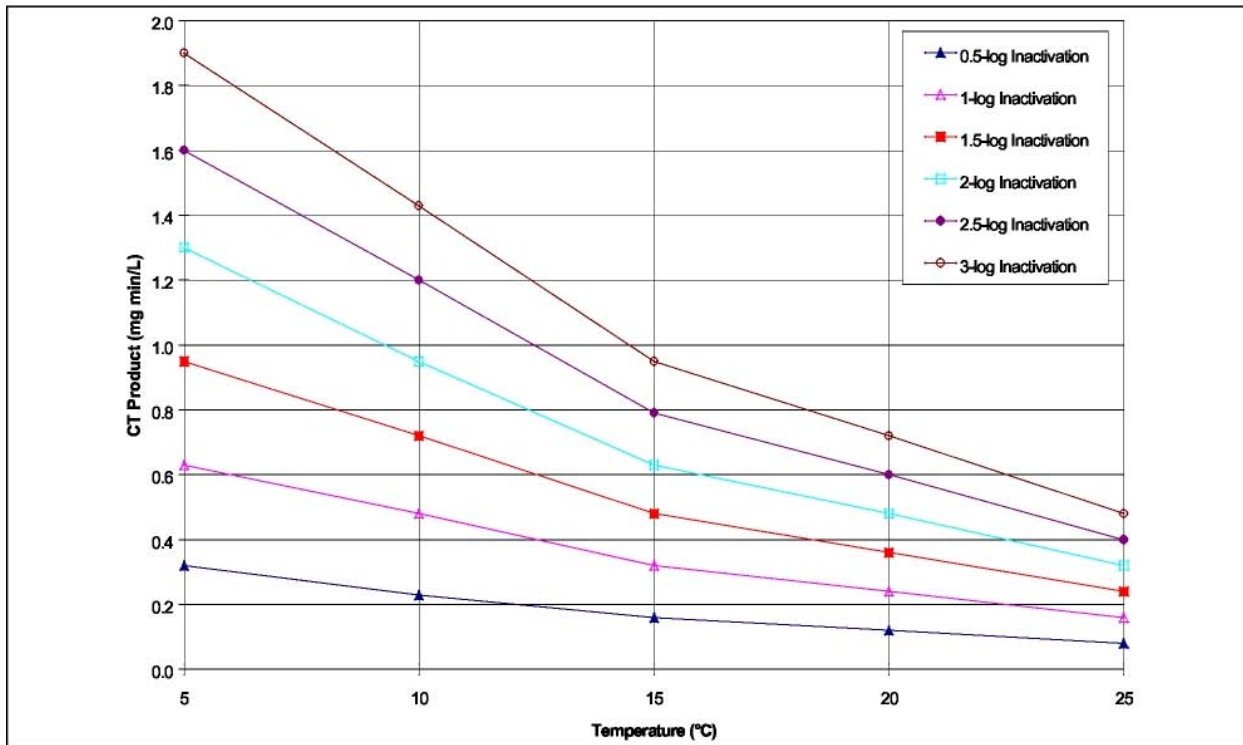
Source: USEPA 2003a

Figure A3: *CT* Values for Inactivation of *Giardia* Cysts by Ozone (pH 6 to 9)

Figure A4: *CT* Values for Inactivation of Viruses by Ozone (pH 6 to 9)

Table A6: *CT* Values (mg·min/L) for *Giardia* Cyst and Virus Inactivation Using Ozone at ≤ 1°C between pH 6 to 9

Pathogens	Log Inactivation			
	1.0	**2.0**	**3.0**	**4.0**
Giardia Cyst	0.97	1.9	2.9	-
Virus	-	0.9	1.4	1.8

Source: MOE 2003

Table A7: *CT* Values (mg·min/L) for *Cryptosporidium* Inactivation by Ozone

Log credit	Water Temperature, ºC									
	<=0.5	**1**	**2**	**3**	**5**	**7**	**10**	**15**	**20**	**25**
0.5	12	12	10	9.5	7.9	6.5	4.9	3.1	2.0	1.2
1.0	24	23	21	19	16	13	9.9	6.2	3.9	2.5
1.5	36	35	31	29	24	20	15	9.3	5.9	3.7
2.0	48	46	42	38	32	26	20	12	7.8	4.9
2.5	60	58	52	48	40	33	25	16	9.8	6.2
3.0	72	69	63	57	47	39	30	19	12	7.4

Source: USEPA 2003a

Table A8: UV Dose (mJ/cm^2) Requirements (With Safety Factor) Based on Validation Testing

	Log Inactivation							
	0.5	**1.0**	**1.5**	**2.0**	**2.5**	**3.0**	**3.5**	**4.0**
Cryptosporidium	7.7	12	17	24	32	42	-	-
Giardia	7.5	11	15	23	30	40	-	-
Virus	63	94	128	161	195	231	263	300

*Source: USEPA 2003b
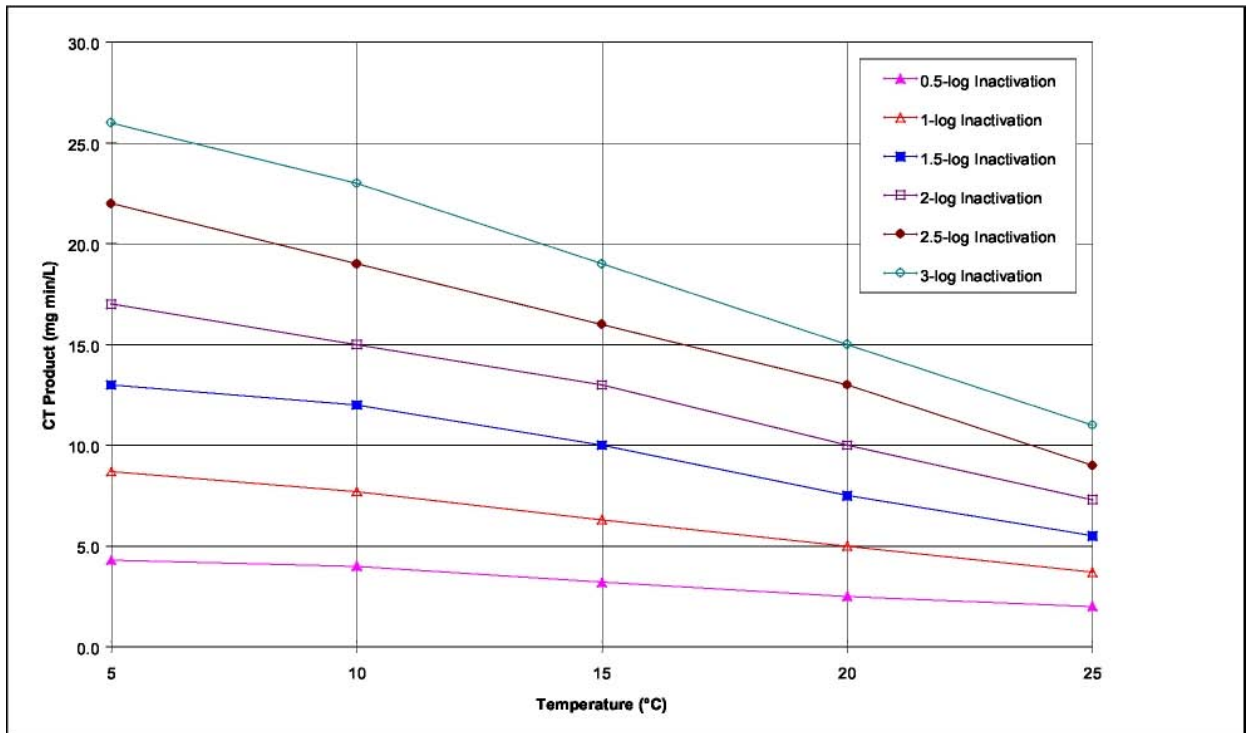
Source: AWWA 1991

Figure A5: *CT* Values for Inactivation of *Giardia* Cysts by Chlorine Dioxide
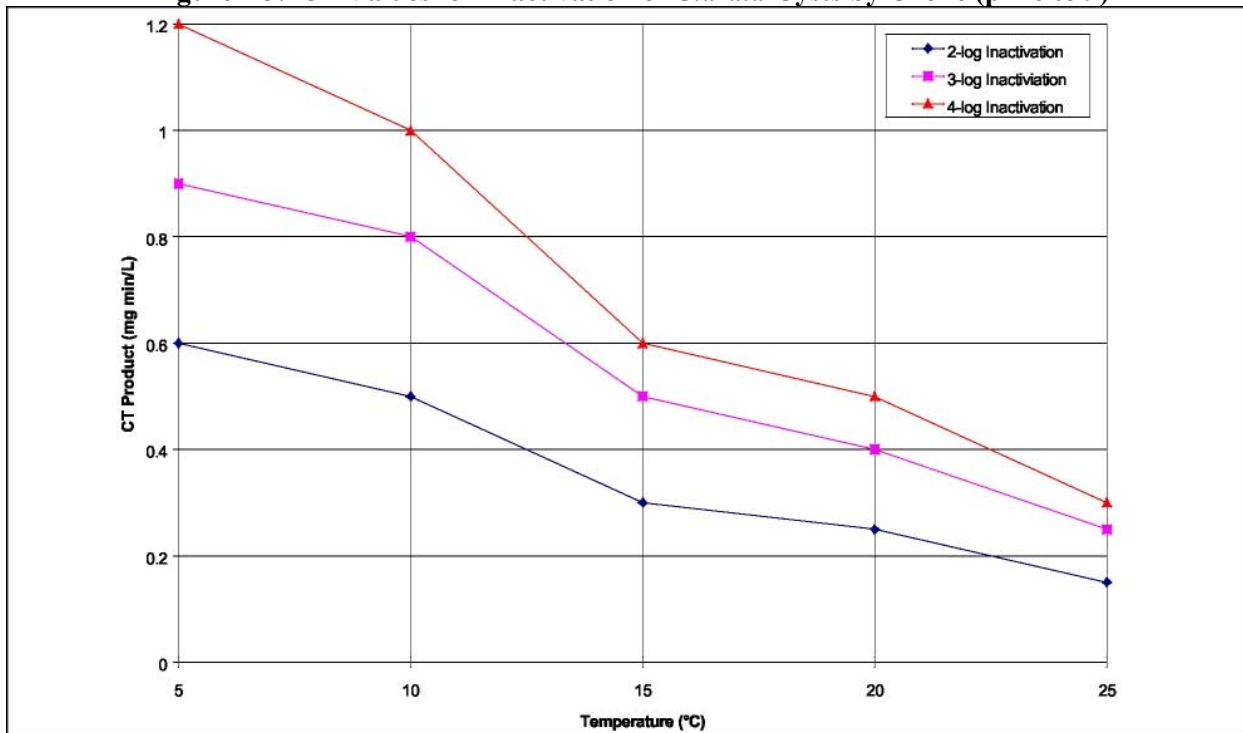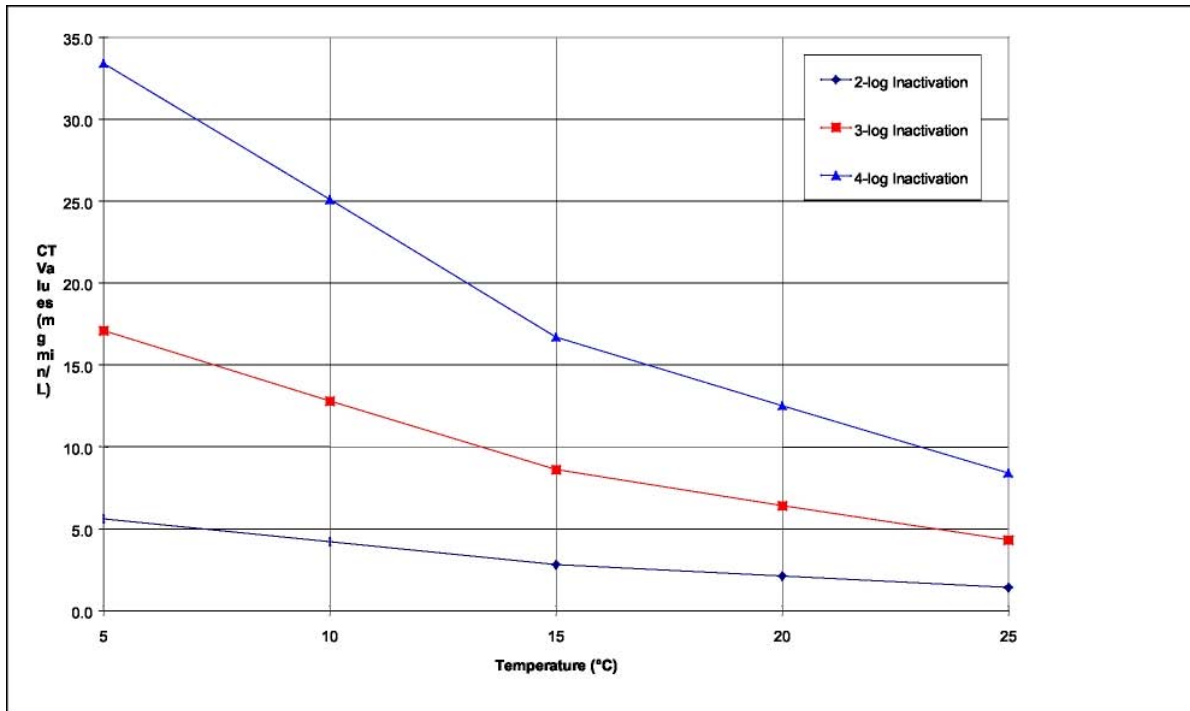
Source: AWWA 1991.

Figure A6: *CT* Values for Inactivation of Viruses by Chlorine Dioxide

Table A9: *CT* Values (mg·min/L) for *Giardia* Cyst and Virus Inactivation Using Chlorine Dioxide at ≤ 1°C between pH 6 to 9

Pathogens	Log Inactivation			
	1.0	**2.0**	**3.0**	**4.0**
Giardia Cyst	21	42	63	-
Virus	-	8.4	25.6	50.1

Source: MOE 2003

Table A10: *CT* values (mg·min/L) for *Cryptosporidium* Inactivation Using Chlorine Dioxide

Log credit	Water Temperature, ºC									
	≤ 0.5	**1**	**2**	**3**	**5**	**7**	**10**	**15**	**20**	**25**
0.5	319	305	279	256	214	180	138	89	58	38
1.0	637	610	558	511	429	360	277	179	116	75
1.5	956	915	838	767	643	539	415	268	174	113
2.0	1275	1220	1117	1023	858	719	553	357	232	150
2.5	1594	1525	1396	1278	1072	899	691	447	289	188
3.0	1912	1830	1675	1534	1286	1079	830	536	347	226

CT values between the indicated temperatures may be determined by interpolation
Source: USEPA 2003a

APPENDIX B
DISINFECTANT CHECKLISTS

The section below is both a general checklist and questionnaire for water system proponents, who wish to use chlorine or alternative disinfectants. This will be used as a tool by the Office of Drinking Water for assessing the water system. ***Note: The document should not be used by the water system as the sole guideline for design. Rather it should be used as very basic guideline for implementing disinfection in their water system.***

1.   Location of water system_____

2.   Is the water system small (<1,000 population) or large (>1,000 population)? _____

3.   Population served_____

4.   Description of the current water treatment system (from source to tap) _____

      _____

5.   Raw water source_____

6.   What are the major potential sources of contamination of the raw water?

      _____

7.   What are the major drinking water concerns currently faced by the community?

      _____

      _____

      _____

8.   What are the changes to water treatment proposed by the water system to mitigate the problems?

      _____

      _____

      _____

9.   Proposed changes to disinfection

      a.   Primary disinfection (circle one or more):
            i.   Chlorine
            ii.   Chlorine Dioxide
            iii.   Ozone
            iv.   Ultraviolet Light
            v.   Other (please specify)
            vi.   None

      b.   Secondary disinfection (circle one or more):
            i.   Chlorine
            ii.   Chloramines
            iii.   Chlorine Dioxide

      iv.   Other (please specify)

      v.   None

10.   Primary disinfection (Based on *CT* tables in Alternative Disinfectant Guidance Document)

    a.   *CT* or *IT* applied

    b.   Log reduction of bacteria

    c.   Log reduction of viruses

    d.   Log reduction of *Giardia*

    e.   Log reduction of *Cryptosporidium*

11.   Water quality characteristics just before the proposed addition of the alternative disinfectants is similar to Table B1 (attached at the end) for at least 95% of the time in a month.

                  Yes _____   No _____

    If no, list the parameters and the values outside of recommended ranges_____

_____

12.   Able to meet standards specified in Manitoba *Drinking Water Quality Standards Regulations* and operating licence.

                  Yes _____   No _____

13.   Able to meet *Guidelines for Canadian Drinking Water Quality*.

                  Yes _____   No _____

14.   Able to achieve the following from the overall water treatment process.

    a.   3-log reduction of *Cryptosporidium*   Yes _____   No _____

    b.   3-log reduction of *Giardia*   Yes _____   No _____

    c.   4-log reduction of viruses   Yes _____   No _____

15.   The water systems have sampling taps before and after disinfection to confirm *CT* calculations

                  Yes _____   No _____

16.   Temperature considered for *CT* calculations   Yes _____   No _____

17.   Piping conforming to AWWA, CSA or CGSB Standards   Yes _____   No _____

18.   Backflow prevention on in-plant line to unit processes or fixture/process isolation

                  Yes _____   No _____

19.   Upstream and downstream isolation valves provided   Yes _____   No _____

20.   Most areas in the distribution system served by
                 looped piping?   Yes _____   No _____

21.   What pipes are critical to getting water to your consumers? _____

_____

22. Is there another way to get water to your consumers if these critical pipes break?

    Yes _____   No _____

    If yes, how? _____

23. How many people will be without water if a pipe breaks and is not looped? _____

24. What pipe repair parts do you have in stock?
    List type and sizes _____

25. How will you get repair parts if you do not have them in storage? _____

    _____

26. Chemicals and coatings in contact with potable water meet NSF standards?

    Yes _____   No _____

27. All finished water reservoirs covered and locked?   Yes _____   No _____

28. How many days can you serve consumers from storage only? _____

29. What happens if a pump station cannot run because of a power outage? _____

30. Redundancy in the system where the spare pumps are located in a different location from the
    working equipment.   Yes _____   No _____

31. Water system monitors consumer complaints.   Yes _____   No _____

32. The water system has a laboratory with sink and appropriate testing equipment.

    Yes _____   No _____

33. The water system has a trained operator (to appropriate level) and an operation and maintenance
    manual.   Yes _____   No _____

34. The water system has an early warning monitoring system to notify an operator of changes in
    water quality characteristics like turbidity, pH, flow, and temperature.

    Yes _____   No _____

35. Alarms and telemetry system provided   Yes _____   No _____

    If yes, provide details of the alarm systems _____

The following sections are applicable for water systems using the respective disinfectants.

A.   <u>Chlorine</u>

A1.   Necessary safety measures (Refer Section 5.3.6)   Yes _____   No _____

A2. Are the following parameters monitored in the distribution system?

Free chlorine residual   Yes _____ No _____

E. Coli   Yes _____ No _____

Trihalomethanes   Yes _____ No _____

A3. Redundancy   Yes _____ No _____

Explain _____

A4. Spill Containment/Scrubbers   Yes _____ No _____

B. <u>Monochloramine</u>

B1. The ratio of Cl_2 to NH_3 ranging from 3:1 to 5:1   Yes _____ No _____

B2. How will the water system control nitrification? _____

_____

_____

B3. Necessary safety measures (Refer Section 5.4.6)   Yes _____ No _____

B4. Chlorine and ammonia gas not stored in same room   Yes _____ No _____

B5. Ammonia gas application points located at least 5 feet away from chlorine feed solution lines.

                                         Yes _____ No _____

B6. Ammonia gas storage tanks protected from direct
sunlight or heat   Yes _____ No _____

B7. Are the following parameters monitored in the distribution system?

Total Chlorine residual   Yes _____ No _____

Free chlorine residual   Yes _____ No _____

HPC   Yes _____ No _____

E. Coli   Yes _____ No _____

Nitrite-N   Yes _____ No _____

B8. Redundancy   Yes _____ No _____

Explain _____

B9 Spill Containment/Scrubbers   Yes _____ No _____

C. <u>Ozone</u>

C1. Bench/Pilot Scale study (for large systems only)   Yes _____ No _____

C2. Ozone destruction unit present   Yes _____ No _____

C3.   Secondary disinfection (Chlorine or Monochloramine)
of the finished water   Yes _____   No _____

C4.   Ozone monitored in the contactor   Yes _____   No _____

C5.   Bromide monitored at the entry of distribution system   Yes _____   No _____

C6.   Ozone generator housed indoors   Yes _____   No _____

C7.   Ambient ozone detector present   Yes _____   No _____

C8.   Have the necessary safety measures (Refer Section 5.5.7)   Yes _____   No _____

C9.   Redundancy   Yes _____   No _____

D.   **Ultraviolet Light**

D1.   Validation done:

    a.   NSF Certified (for small drinking water systems)   Yes _____   No _____
    b.   Collimated Beam Test (for large systems)   Yes _____   No _____
    c.   Biodosimetry of Full-Scale Reactors
       (for large systems)   Yes _____   No _____

D2.   Secondary disinfection (Chlorine or Monochloramine) of the finished water

                                                          Yes _____   No _____

D3.   UV transmittance monitor calibration   Yes _____   No _____

D4.   Fouling potential of the lamps assessed   Yes _____   No _____

D5.   Lamp cleaning system (manual or automatic)   Yes _____   No _____

D6.   UV intensity sensors   Yes _____   No _____

D7.   Monitoring   Yes _____   No _____

    Explain _____

D8.   Have the necessary safety measures (Refer Section 5.6.8)   Yes _____   No _____

D9.   Standby power provisions   Yes _____   No _____

E.   **Chlorine Dioxide**

E1.   Bench/Pilot scale studies (for large systems)   Yes _____   No ____

E2.   Secondary disinfection (Chlorine or Monochloramine) of the finished water

                                                          Yes _____   No _____

If no, can the ClO_2 provide required residual protection
in the water of the distribution system before it reaches
the consumers?   Yes _____ No _____

E3.   Indoor chemical storage   Yes _____   No _____

E4.   Necessary safety measures (Refer Section 5.7.7)   Yes _____   No _____

E5.   Chlorine dioxide monitoring at distribution system entry point

                                                           Yes _____   No _____

       Details_____

E6.   Chlorite monitoring at distribution system entry point   Yes _____   No _____

       Details_____

E7.   Alarms and telemetry system provided   Yes _____   No _____

       If yes, provide details of the alarm systems_____

       _____

E8.   Redundancy   Yes _____   No _____

       Explain _____

**Table B1: Typical Water Quality Characteristics for
Application of Alternative Disinfectants**

Parameters	*Chlorine*	Chloramines	Ozone	Chlorine Dioxide	UV
Turbidity (NTU)	≤ 1	≤ 1	≤ 5	≤ 1	≤ 1
Total Coliform (organisms/100mL)	≤ 100	≤ 100	≤ 100	≤ 100	≤ 100
E. Coli (organisms/100mL)	≤ 20	≤ 20	≤ 20	≤ 20	≤ 20
TOC (mg/L)	≤ 4	≤ 4	≤ 4	≤ 4	≤ 4
UV transmittance (%)	NA	NA	NA	NA	≥ 75
Suspended Solids (mg/L)	≤ 10	≤ 10	≤ 10	≤ 10	≤ 10
pH	5.5 - 7.5	6.5 – 9.5	6.5 – 9.5	6.5 – 9.5	6.5 – 9.5
Colour (TCU)	≤ 15	≤ 15	≤ 15	≤ 15	≤ 5
TDS (mg/L)	≤ 650	≤ 650	≤ 650	≤ 650	≤ 650
Bromides (mg/L)	NA	NA	≤ 1 mg/L	NA	NA
Dissolved Iron (mg/L)	≤ 0.3 mg/L	≤ 0.3 mg/L	≤ 0.3 mg/L	≤ 0.3 mg/L	≤ 0.3 mg/L
Dissolved Copper (mg/L)	≤ 1 mg/L	≤ 1 mg/L	≤ 1 mg/L	≤ 1 mg/L	≤ 1 mg/L
Dissolved Manganese (mg/L)	≤ 0.05 mg/L	≤ 0.05 mg/L	≤ 0.05 mg/L	≤ 0.05 mg/L	≤ 0.05 mg/L
Odour (H_2S)	ND	ND	ND	ND	ND
Blue-Green Algae or Total microcystins (µg/L)	≤ 1.5	≤ 1.5	≤ 1.5	≤ 1.5	≤ 1.5

Note: NA=Not applicable
ND=Non-detectable