Disinfection Technologies for Potable Water and Wastewater Treatment: Alternatives to Chlorine Gas

Prepared by:

Leslie Snowden-Swan
John Piatt
Ann Lesperance

Pacific Northwest National Laboratory

Prepared for:

U.S. Army Forces Command
Air Quality Division

July 1998

Disinfection Technologies for Potable Water and Wastewater Treatment: Alternatives to Chlorine Gas

Prepared by:

Leslie Snowden-Swan
John Piatt
Ann Lesperance

Pacific Northwest National Laboratory

Prepared for:

U.S. Army Forces Command
Air Quality Division

July 1998

Executive Summary

Several FORSCOM sites are evaluating conversion of their potable water and wastewater treatment systems from gaseous chlorine to an alternative technology. The principal motivation for this evaluation is the requirement for installations to assess the risks associated with gaseous chlorine and prepare a Risk Management Program. According to the Clean Air Act, a Risk Management Plan describing the installation's Risk Management Program must be submitted to EPA and disclosed to the public by June 1999 if a site stores quantities of chlorine that exceed the regulated threshold amount. This requirement has raised awareness of the health risks posed by gaseous chlorine, the increasingly stringent requirements for safe operation of systems using gaseous chlorine, and concern about the vulnerability of gaseous chlorine systems to sabotage.

Because of chlorine's inherent toxicity, large gaseous chlorination systems pose a health risk to facility operators and a potential risk to military personnel and the public. These systems are already required to have in place accidental release prevention and emergency response programs that meet Occupational Safety and Health Administration (OSHA) process safety requirements and to comply with Environmental Protection Agency (EPA), and state regulations to ensure safe water and protection of the environment. Military installation personnel are dedicated to environmental stewardship and the safety and well-being of those affected by military actions. In addition to meeting regulatory requirements for water and wastewater treatment systems, they are currently considering alternative technologies to gaseous chlorine as a means of reducing risk to the environment, workers and the public.

The purpose of this paper is to provide information that will help FORSCOM installations understand the trade-offs involved in a decision to replace gaseous chlorine with another disinfection technology. It describes the characteristics of an ideal disinfection technology and compares the performance of seven currently available alternatives relative to those characteristics.

An ideal potable and wastewater disinfection technology:

- Kills all potential pathogens in the water;
- Adds no toxic compounds to the water
- For potable water, provides lasting residual disinfectant without excess chemicals
- Is safe, easy, and inexpensive to use
- Meets current and upcoming regulations.

The following seven currently available alternatives are evaluated in relation to those characteristics:

- Sodium hypochlorite (both purchased and on-site generation)
- Calcium hypochlorite
- Mixed oxidant generation (MIOX^{tm} Co.)
- Chlorine dioxide (ClO_2),
- Chloramination
- Ozone (O_3)
- Ultraviolet Light (UV)

All of these disinfection technologies are currently available for primary disinfection of potable water and wastewater. They are scalable to virtually any size of system, either by the use of differently-sized units or combinations of standard units. While system designs tend to be standardized, some level of engineering will usually be required to integrate any of these technologies into existing water treatments systems. Ease, speed of procurement, and capital outlay are important considerations for FORSCOM installations. Some of the alternative technologies have contracts with the General Services Administration (GSA) and are available from the Federal Supply Schedule under Water Purification Equipment (FSC Group 46, Part I, Section A, FSC Class 4610) through listed contractors. In addition, some manufacturers offer lease-purchase type agreements that can spread the costs of procuring a technology over two or three years.

Chlorine-based technologies (sodium hypochlorite; calcium hypochlorite; mixed oxidant generation; chlorine dioxide; and chloramination) can provide quick and simple replacements for gaseous chlorination systems. On-site generation of sodium hypochlorite and mixed oxidants from a brine solution eliminate both public and worker exposures to toxic chemicals. However, on-site generation of sodium hypochlorite produces hydrogen, which presents a fire or explosion hazard if not properly vented. An advantage of the mixed oxidant technology is that it produces fewer disinfection byproducts than gaseous chlorine, which can be important for installations whose current disinfection byproduct levels will not meet the more stringent EPA standards.

The non-chlorine-based technologies (ozone and ultraviolet light) have relatively high capital costs. Because ozone is a toxic chemical, ozone systems require monitoring and the ability to convert ozone to oxygen in case of a leak. Consequently, ozone systems have the highest capital costs of the alternatives considered, and do not eliminate potential hazardous exposures of workers. However, ozone provides the best disinfection capability of the alternatives examined. Both ozone and UV technologies have an advantage for wastewater applications because they disinfect without requiring dechlorination prior to discharge. Neither ozone nor UV produces hazardous disinfectant by-products. However, if either of these technologies is used to disinfect drinking water, chlorine or a chlorine-based alternative must be used to provide the residual, or secondary, disinfection capability needed in the water distribution system. In addition, UV is not approved as a treatment for surface water sources that may contain hazardous cysts.

The following table summarizes the performance of the baseline and alternative disinfection technologies on key attributes.

Table i. Performance of Disinfection Technologies on Key Characteristics

	Baseline Cl_2	Alt. 1 NaOCl/ On-site- NaOCl	Alt. 2 $Ca(OCl)_2$	Alt. 3 MIOX^{tm}	Alt. 4 ClO_2	Alt. 5 Chloramines	Alt. 6 O_3	Alt.7 UV
Disinfection Capability:[1] Bacteria	Good	Good	Good	Good	Good	Poor	Very Good	Very Good
Viruses	Poor	Poor	Poor	Good	Good	Poor	Very Good	Fair
Cysts	Poor	Poor	Poor	Fair[1]	Fair[1]	Poor	Good	No effect
Generation of Hazardous Disinfection by-products	Yes - THMs And HAA5	Yes- THMs and HAA5	Yes- THMs and HAA5	Yes, but less THMs than Cl_2	Yes, but less THMs than Cl_2 Chlorite/ chlorate produced	Yes, but less THMs than Cl_2	Yes, Bromine Insig. Levels THMs formed	None
Persistent Residual	Good	Good	Good	Good- (longer than Cl^2)	Fair	Very Good	None (good for ww)	None (good for ww)
Safety Concerns	High	Low (for on-site)- Medium	Low	Low	Medium- High[2]	Medium	Medium	Low
Complexity of Operations/ Maintenance)	Minimal	Minimal	Moderate[3]	Moderate	Moderate	Minimal	Moderate	Minimal
Size Applicability	All sizes	All sizes	Small- medium (cost)	All sizes	Small- medium	All sizes	Medium- large	Small- medium
Relative Cost	Low	Low	Moderate	Low	Moderate	Low	High	Moderate
Long Term Applicability For:[5] Potable Water	Low (safety issues)	Medium	Medium	Medium	Medium	Effective only for residual purposes	Medium- must have residual	Medium- must have residual
Waste-water	Medium	Medium	Medium	Medium	Low (cost)	None	High	High

1. Still may require filtration prior to discharge of wastewater.
2. Depending on the method used to generate chlorine dioxide, safety concerns can range from high to moderate.
3. Handling of Ca(OCl)2 is generally more labor-intensive than liquid (i.e. NaOCl)
4. From USEPA Wastewater Disinfection Manual (1986) and communication with equipment manufacturers/vendors.
5. Ability to meet upcoming standards.

Table of Contents

Executive Summary ii
Chapter 1 Introduction 1
Chapter 2. Implications of EPA Regulatory Requirements 5
Drinking Water System Regulations 5
Wastewater System Regulation 7
Chapter 3. Chlorine Gas: The Baseline Technology 9
Advantages 9
Disadvantages 9
Costs 11
Chapter 4. Description of Alternative Disinfection Technologies 12
Alternative 1: Sodium Hypochlorite (“Liquid Chlorine” or Bleach) 12
Advantages 13
Disadvantages 13
Costs 14
Alternative 2: Calcium Hypochlorite (“Solid Chlorine”) 15
Advantages 15
Disadvantages 15
Costs 15
Alternative 3: MIOX^tm (Mixed Oxidant) 17
Advantages 17
Disadvantages 18
Costs 18
Alternative 4: Chlorine Dioxide (ClO_2) 20
Advantages 21
Disadvantages 21
Costs 22
Alternative 5: Chloramination 24
Advantages 24
Disadvantages 25
Costs 25

Alternative 6: Ozone (O_3) 26
Advantages 27
Disadvantages 28
Costs 29
Alternative 7: Ultraviolet (UV) Light 31
Advantages 31
Disadvantages 31
Costs 32
Chapter 5. Comparisons Across Technologies 33
Performance Comparisons 33
Cost Estimates for Alternative Disinfection Technologies 35
Chapter 6: Summary 37

Further Reading 39
References 39
APPENDIX A. Demonstrated Applicability of Alternative Disinfection Technologies and Contacts for Technologies 41
Sodium Hypochlorite (NaOCl) 41
On-Site NaOCl 41
Calcium Hypochlorite ($Ca(OCl)_2$ 41
MIOX^{tm} -- Potable Water 42
MIOX^{tm} -- Wastewater 42
Chlorine Dioxide (ClO_2) 43
Chloramination 44
Ozone (O_3) 44
Ultraviolet (UV) 44

List of Tables

Table i. Performance of Disinfection Technologies on Key Characteristics …………………v

Table 1. Approximate Costs for Gaseous Chlorine Technology (Potable water, 1.2 MGD, 1 ppm chlorine dose) 11

Table 2. Approximate Costs: Gaseous Chlorine and Sodium Hypochlorite (NaOCl) Technology (Potable water, 1.2 MGD, 1 ppm chlorine dose) 14

Table 3. Approximate Costs: Gaseous Chlorine and Calcium Hypochlorite ($Ca(OCl)_2$) Technology (Potable water, 1.2 MGD, 1 ppm chlorine dose) 16

Table 4. Approximate Costs: Gaseous Chlorine and MIOX^{tm} Technology (Potable water, 1.2 MGD, 1 ppm chlorine dose) 19

Table 5. Approximate Costs: Gaseous Chlorine and Chlorine Dioxide(ClO_2) Technology (Potable water, 1.2 MGD, 1 ppm chlorine dose) 23

Table 6. Approximate Costs: Gaseous Chlorine and Ozone Technology (Potable water, 1.2 MGD, 1 ppm chlorine dose) 30

Table 7. Approximate Costs: Gaseous Chlorine and Ultraviolet Light Technology (Potable water, 1.2 MGD, 1 ppm chlorine dose) 32

Table 8. Performance of Disinfection Technologies on Key Characteristics........ 34

Table 9. Approximate Costs for Alternative Disinfection Technologies (1.2 MGD, 1 ppm chlorine dose) 35

Alternative Disinfection Technologies to Chlorine Gas for Potable Water and Wastewater Treatment

1. Introduction

Several FORSCOM sites are evaluating conversion of their potable water and wastewater treatment systems from gaseous chlorine to an alternative technology. The principal motivation for this evaluation is the requirement for installations to assess the risks associated with gaseous chlorine and prepare a Risk Management Program. According to the Clean Air Act Amendment 112(r), a Risk Management Plan describing the installation's Risk Management Program must be submitted to EPA and disclosed to the public by June 1999 if a site stores quantities of chlorine that exceed the regulated threshold amount. This requirement has raised awareness of the health risks posed by gaseous chlorine, the increasingly stringent requirements for safe operation of systems using gaseous chlorine, and concern about the vulnerability of gaseous chlorine systems to sabotage.

Because of chlorine's inherent toxicity, large gaseous chlorination systems pose a health risk to facility operators and a potential risk to military personnel and the public. These systems are already required to have in place accidental release prevention and emergency response programs that meet Occupational Safety and Health Administration (OSHA) process safety requirements and to comply with Environmental Protection Agency (EPA), and state regulations to ensure safe water and protection of the environment. These programs are required under the Occupational Safety and Health Administration's (OSHA's) Rule for

Process Safety Management of Highly Hazardous Chemicals (29 CFR 1910.119) and the Environmental Protection Agency's (EPA's) standard on Chemical Accident Prevention Provisions (40 CFR Part 68).

The purpose of this paper is to provide information to understand trade-offs involved in replacing gaseous chlorine with an alternative disinfection technology.

Military installation personnel are dedicated to environmental stewardship and the safety and well-being of those affected by military actions. In addition to meeting regulatory requirements for water and wastewater treatment systems, installations are currently considering alternative technologies to gaseous chlorine as a means of reducing risk to the environment, workers and the public.

The purpose of this paper is to provide information that will help FORSCOM installations understand the trade-offs involved in a decision to replace gaseous chlorine with another disinfection technology. It describes the characteristics of an ideal disinfection technology and compares the performance of seven currently available alternatives relative to those characteristics. An ideal potable and wastewater disinfection technology:

- kills all potential pathogens in the water;
- adds no toxic compounds to the water
- for potable water, provides lasting residual disinfectant without excess chemicals
- is safe, easy, and inexpensive to use
- meets current and upcoming regulations.

The following seven currently available alternatives are evaluated in relation to those characteristics:

- Sodium hypochlorite (both purchased and on-site generation)
- Calcium hypochlorite

- Mixed oxidant generation (MIOX^{tm} Co.)
- Chlorine dioxide (ClO_2),
- Chloramination
- Ozone (O_3)
- Ultraviolet Light (UV)

This paper summarizes factors leading FORSCOM installations to consider alternatives to their existing gaseous chlorine water treatment technology and describes how currently available alternatives compare to gaseous chlorine on:

- disinfection capability (bactericidal, virucidal, cysticidal)
- generation of hazardous disinfection by-products
- persistent residual
- safety concerns
- complexity of operations and maintenance
- size applicability
- relative cost
- long term applicability for potable and wastewater systems

All of the disinfection technologies discussed are:

- currently available
- scalable to a system of any size

All of these disinfection technologies are currently available for primary disinfection of potable water and wastewater. They are scalable to a system of any size, either by the use of differently-sized units or combinations of standard units. While system designs tend to be standardized, some level of engineering will usually be required to integrate any of these technologies into existing water treatments systems.

Ease, speed of procurement, and capital outlay are important considerations for FORSCOM installations. Some of the alternative technologies have contracts with the General Services Administration (GSA) and are available from the Federal Supply Schedule under Water Purification Equipment (FSC Group 46, Part I, Section A, FSC Class

4610) through listed contractors. In addition, some manufacturers offer lease-purchase type agreements that can spread the costs of procuring a technology over two or three years. Where this information was known, it is included in the descriptions of the alternatives. At this time, no consolidated list of suppliers with GSA contracts exists. However, inquiries can be directed to the installation's legistics or supply organizations.

Estimation of costs was not derived from detailed design and cost analyses.

To help FORSCOM staff evaluate the seven alternatives, operating and capital costs were estimated for chlorine gas and each alternative disinfection technology. *It is important to note that these costs were not derived from detailed design and cost analyses and consequently represent only order-of-magnitude, comparative estimates.* The costs were estimated for:

- a potable water treatment plant
- capacity of 1.2 million gallons per day (MGD)
- operating 24 hours per day
- chlorine dose of 1 ppm (or, for alternatives, a dose that would produce comparable disinfection results)
- electricity rates of $0.042 per kilowatt hour (average for Washington State).

Although the configuration and thus the cost of equipment and products for wastewater systems is highly influenced by water characteristics, state and regional variation of cost, and quality and volume of water, these cost estimates also provide an approximate basis of comparison across technologies for wastewater systems when the costs of dechlorination are added to the chlorine-based systems.

2. Implications of EPA Regulatory Requirements

Changing drinking water and wastewater rules will make it increasingly difficult for facilities to continue to use chlorination disinfection technologies.

Changing drinking water rules, along with stricter state regulations on wastewater contaminants will make it increasingly difficult for facilities to continue to use chlorination disinfection technologies in the future. It is likely that alternatives to gaseous chlorine that provide safety advantages but do not provide advantages with respect to disinfection by-product production or virucidal/cysticidal capability will require modification or complete changeout to address these issues as the new regulations come into effect.

Drinking Water System Regulations

Microbial Contaminants:

In 1991, the Surface Water Treatment Rule (as part of the federal Safe Drinking Water Act), expanded the array of contaminants that drinking water treatment systems must disinfect. Viruses and *Giardia lamblia* cysts were added to the list. In 1993, 100 deaths and over 300,000 illnesses linked to chlorine-resistant *Cryptosporidium* in the Milwaukee's water system prompted the EPA to develop the Interim Enhanced Surface Water Treatment Rule, which is expected to be promulgated in November 1998. This new rule will establish more stringent guidelines for microbial contaminants, including the inactivation of *Cryptosporidium.* The Long-Term Enhanced Surface Water Treatment Rule, to be promulgated by EPA in November 2000, will be more stringent still.[1] [USEPA Office of Ground Water and Drinking Water 1997].

---

[1] For additional information about this rule see www.epa.gov/OGWDW/mdbp/mdbp.html

Chlorine and its toxic by-products are subject to increasingly stringent EPA guidelines.

Long-term viability of chlorine-based technologies will be affected by efficient, cost-effective processes to reduce by-product production.

By-product contaminants:

Chlorine and some of its disinfection by-products have been linked to cancer and other adverse health effects. Trihalomethanes, or THMs, (formed when chlorine reacts with humic and fulvic organic compounds, such as soil and plant materials) and the haloacetic acids, or HAA5 (i.e., acetylene gas combined with water vapor) cause certain cancers in laboratory animals. For this reason, chlorine and these toxic by-products are subject to increasingly stringent EPA guidelines. THMs are currently regulated at a total maximum contaminant level of 0.1 mg/l in drinking water. This maximum contaminant level is expected to be reduced to 0.080 mg/l as part of the Stage 1 Disinfectant/Disinfection Byproduct Rule (D/DBP Rule), to be promulgated in November 1998,[2] and to 0.03 mg/l in the Stage 2 D/DBP Rule, to be promulgated in May 2002. The HAA5 have a proposed Stage 1 standard of 0.060 mg/l [USEPA, draft 1998] and a Stage 2 standard of 0.04 mg/l.

The long-term viability of chlorine-based technologies will be affected by the availability of efficient, cost-effective processes to reduce by-product production. Most research has been focused on developing more cost-effective, efficient processes to remove the precursors of these toxic by-products. Several technologies to minimize/destroy precursors of THMs and HAA5 are currently available; others are under development.

[2] Other compounds to be included in the Stage 1 Rule are haloacetic acids (0.060 mg/L), also byproducts of chlorination; bromate (0.010 mg/L), a byproduct of ozonation when bromide is present in water; and chlorite (1.0 mg/L), a byproduct of chlorine dioxide disinfection.

Wastewater System Regulation

Microbial Contaminants:

Wastewater discharge limits on microbial concentrations are ultimately regulated at the state level, but are influenced by the following EPA guidelines [WEF, Wastewater Disinfection; U.S. EPA, 1992]:

- Minimum of five samples over a 30-day period
- Fecal coliform content of primary contact recreation waters not to exceed a geometric mean of 200 MPN(most probable number)/100 ml, and
- Ten percent of the total samples during any 30-day period not to exceed 400 MPN/100ml.

Chlorine and its byproducts are a concern for wastewater treatment systems that discharge into receiving waters.

Most states currently use these guidelines; however, the specific limits for microorganism concentrations vary greatly depending on the different state regulations and on the characteristics of the receiving body of water. For example, state fecal coliform standards range from 2.2 MPN/100 ml to 5,000 MPN/100 ml.

Residuals:

Most wastewater systems using the chlorine-based disinfection technology require dechlorination prior to discharge.

Chlorine residuals have been found to be acutely toxic to some species of fish at very low levels (USEPA, 1986). In addition, other toxic or carcinogenic chlorinated compounds can build up in the tissues of aquatic wildlife and possibly contaminate drinking water supplies. For these reasons, chlorine and its byproducts are a concern for wastewater treatment systems that discharge into receiving waters. These compounds are currently subject to state regulations which can vary significantly. Federal standards applying to military bases require chlorine content in discharged wastewaters to be less than 0.5 mg/[Ft. Lewis NPDES permit]. In order to meet this requirement, most chlorination facilities (including the hypochlorite-based systems) must use a dechlorination technology prior to discharge.

3. Chlorine Gas: The Baseline Technology

Chlorine gas (Cl_2) technology has been the primary method of disinfecting water in this country for nearly a century.

Chlorine gas (Cl_2) technology has been the primary method of disinfecting water in this country for nearly a century. Chlorine gas is used in about 87 percent of US municipal water treatment facilities that disinfect (Naude, A, 1997). While some treatment facilities have retired chlorine gas technology, the vast majority have not, given the familiarity, perceived economic benefits and general disinfection performance of this method.

With this disinfection method, chlorine is absorbed and distributed throughout the water being treated and the target organisms are killed. Chemically, this process is termed hydrolyzation, with the organisms killed by the resulting hypochlorous acid (or hypochlorite ion at high pH):

$$Cl_2 + H_2O \rightarrow HOCl + HCl$$

Chlorine is inexpensive, an excellent bacterial disinfectant with well understood chemistry and design and operating characteristics.

Advantages:

Chlorine is inexpensive, is an excellent bacterial disinfectant requiring short to moderate contact times, and its chemistry is very well understood. It has a very large established base, and its design and operating characteristics are well understood.

Although disinfection with chlorine gas has advantages, several disadvantages have become increasingly important.

Disadvantages:

Although disinfection with chlorine gas has advantages, several disadvantages have become increasingly important. Safety and liability concerns have been a key reason for facilities to switch to alternative technologies. In addition, chlorine is ineffective against *Giardia lamblia* cysts and some strains of *Cryptosporidium*, microbes that have recently caused illness and death in this country.

Chlorine is extremely volatile and hazardous, requiring specific safety percautions.

Chlorine is an extremely volatile and hazardous chemical and requires specific precautions for it to be shipped, stored, and used safely. For example, chlorine gas systems located near populated areas or other facilities may require the additional safety precaution of placing the chlorine gas cylinders in an enclosed building that is equipped with a scrubber system to capture and remove any escaping chlorine gas.

Systems using chlorine gas also have the disadvantage of producing toxic disinfection by-products. If these levels are too high, the system must be modified to reduce by-product production. One strategy to minimize THM production is to relocate the chlorination process, placing it after sedimentation, coagulation, and filtration and just prior to filtration [USEPA draft, 1998]. Although enhanced coagulation, granular activated carbon adsorption, or membrane filtration prior to disinfection can further reduce by-product production, granular activated carbon and membrane filtration tend to be cost-prohibitive [USEPA draft, 1998]. See Figure 1 for an illustration of a typical surface/water treatment system. Preozonation, used to oxidize organics prior to the sand filtration, and carbon adsorption processes to remove byproduct precursors, are sometimes used to extend the life of the carbon column and reduce costs.

To meet wastewater discharge standards, most wastewater treatment systems using chlorine gas must use a dechlorination technology to remove residual chlorine prior to discharge.

To meet wastewater discharge standards, most wastewater treatment systems using chlorine gas must use a dechlorination technology to remove residual chlorine prior to discharge. This increases the cost of treatment. Four dechlorination technologies are currently available: 1) sodium dioxide (not a good alternative choice, since it creates a hazardous waste by-product), 2) sodium bisulfate, 3) sodium thiosulfate and 4) ascorbic acid (Vitamin C). Granular ascorbic acid which is effective dissolves quickly and is least expensive of the four alternatives

($2-$3 per pound), can be fed into the system through a calibrated grain feeder[1]

Costs:

The following table illustrates the impact of adding scrubbers on capital costs.

Table 1. Approximate Costs for Gaseous Chlorine Technology (Potable water, 1.2 MGD, 1 ppm chlorine dose)

	Cl_2 with scrubbers 150# cylinders	Cl_2 without scrubbers 150# cylinders
Capital	$65,000	$15,000
Operating	3,600	3,600
Maintenance	2,600	2,600

Source: Matheson Gas Products

[1] As with other oxidants, ascorbic acid creates a slight oxygen demand.

This section describes seven available alternative technologies including:

- advantages
- disadvantages
- relative costs.

Sodium hypochlorite (NaOCl):

- is a liquid form of chlorine that achieves disinfection results similar to chlorine gas
- has gained popularity as a viable alternative to chlorine gas.

4. Description of Alternative Disinfection Technologies

In the following section, seven available alternative disinfection technologies are briefly described and the advantages, disadvantages, and relative costs and maintenance issues associated with each are summarized.

Alternative 1: Sodium Hypochlorite ("liquid chlorine" or bleach)

Sodium hypochlorite (NaOCl) is known as a liquid form of chlorine that achieves results similar to chlorine gas disinfection. NaOCl has long been used as a disinfectant and has gained popularity in the past few decades as a viable alternative to chlorine gas for drinking water and wastewater treatment. The chemistry of disinfection is essentially the same as with chlorine gas, with the hypochlorite ion (predominant at $pH>8.5$) or hypochlorous acid (predominant at $pH<6.5$) acting on cell walls to eventually kill the target organisms.

NaOCl can be commercially supplied or generated on-site, the latter being the safer of the two methods for handling reasons. In on-site generation, salt is dissolved with softened water to form a concentrated brine solution that is subsequently diluted and passed through an electrolytic cell to form sodium hypochlorite. During electrolysis, hydrogen is also formed, which, because of its explosive nature, may need to be vented. Although on-site generation generally requires a higher capital investment, its lower handling costs and reduced liability may make it more desirable than supplied NaOCl.

A newer technology for on-site production is marketed by Aquasafe Technology Pty Ltd, Sydney, Australia. This technology, which has been implemented at over 50 sites internationally, generates hypochlorite in solution using only 10% hydrochloric acid and the water to be treated. The THM concentration in the drinking water treated by the Sydney Palm Beach Reservoir facility, which uses this technology, was below 0.02 mg/l. This is lower than the THM level expected from chlorine gas treatment.

When using sodium hypochlorite for wastewater treatment, a dechlorination process subsequent to disinfection is usually required to reduce the chlorine residual being discharged to receiving waters. Typically, dechlorination is achieved by the addition of sulfur dioxide, sodium bisulfite, sodium thiosulfate, or ascorbic acid.

Sodium hypochlorite has similar disinfectant efficiency and residual performance as chlorine gas while reducing the handling and storing hazards.

Advantages:

Disinfection with sodium hypochlorite has similar disinfectant efficiency and residual performance as chlorine gas, but reduces the hazards associated with the handling and storing of chlorine gas. If generated on-site, no hazardous chemicals are used, the only components being high grade salt (NaCl) and softened water. With on-site production, NaOCl solutions are less concentrated and less hazardous (typically a 1% concentration) than the standard supplied solution (14% concentration).

Sodium hypochlorite is a hazardous and corrosive substance, yet offers no advantage over chlorine gas with regard to disinfection capability and disinfection

Disadvantages:

Although safer to handle than chlorine gas, NaOCl is a hazardous and corrosive substance. At the standard supplied concentration (14%), storage and handling of NaOCl requires process safety procedures and containment to avoid exposure to workers and the environment and to prevent loss of potency through exposure to air, which causes it to deteriorate.[1] If kept sealed, shelf life is not a factor. It can be easily stored 1-2 months. On-site generation techniques generally avoid these

[1] If kept sealed, shelf life is not a factor. It can be easily stored 1-2 months.

problems. Because its disinfection mechanism is essentially the same as that of chlorine gas, NaOCl generally offers no advantage over chlorine gas with regard to disinfection capability (i.e., *Giardia, and Cryptosporidium*), and disinfection by-product formation.

Costs:

The following table highlights the significant capital cost savings associated with the off-site generation of NaOCl; but increased operating and maintenance costs. On-site generation of NaOCl capital costs are higher than off-site generation of NaOCl and Cl_2 without scrubbers but much less than Cl_2 with scrubbers.

Table 2. Approximate Costs: Gaseous Chlorine and NaOCl Technology (Potable water, 1.2 MGD, 1 ppm chlorine dose)

	Cl_2 with scrubbers 150# cylinders	Cl_2 without scrubbers 150# cylinders	NaOCl (Off-site Generated)	NaOCl (On-site Generated)
Capital	$65,000	$15,000	$2,500	$18,000
Operating	3,600	3,600	4,400	1,500
Maintenance	2,600	2,600	5,000	1,600

Sources: Matheson Gas Products (Cl_2); Van Waters and Rogers (NaOCl)

Alternative 2: Calcium Hypochlorite ("solid chlorine")

Calcium hypochlorite is:
- similar to sodium hypochlorite in disinfection properties
- appropriate for both drinking water and wastewater applications.

Calcium hypochlorite ($Ca(OCl)_2$) is essentially a solid that is used in place of liquid NaOCl. It is very similar to NaOCl in disinfection properties, but has the distinct advantage of being safer to handle. Commercial grades of $Ca(OCl)_2$ generally contain about 70% available chlorine. It is appropriate for both drinking water and wastewater applications.

Advantages:

Calcium hypochlorite is safer than sodium hypochlorite and chlorine gas and it also has excellent stability.

Because it is a solid, $Ca(OCl)_2$ is safer than NaOCl and chlorine gas. It also has excellent stability when kept in dry storage, maintaining its potency well over time.

Disadvantages:

Calcium hypochlorite offers no disinfection efficiency advantages or disinfection by-product advantages over chlorine gas or sodium hypochlorite.

Because the chemistry is so similar to chlorine gas and NaOCl ("liquid chlorine"), this method offers no disinfection efficiency advantages (i.e., *Giardia and Cryptosporidium* kill rates) nor disinfection by-product advantages. Although solid $Ca(OCl)_2$ is more stable and safer to handle than its liquid counterpart NaOCl, it is corrosive and hygroscopic (i.e., readily absorbs moisture), reacting slowly with moisture in the air to form chlorine gas if not stored in air-tight containers. Therefore, containers of $Ca(OCl)_2$ must be completely sealed or emptied entirely. As with chlorine gas and NaOCl, wastewater systems using $Ca(OCl)_2$ generally require dechlorination after disinfection to reduce chlorine discharges to receiving waters.

Costs:

Chemical costs for calcium hypochlorite are typically 1.5-2.5 times higher than supplied NaOCl [USEPA, 1990], due to the energy intensive process required to produce calcium hypochlorite. Equipment, operating, and maintenance costs are generally comparable for systems using $Ca(OCl)_2$ and NaOCl.

Table 3. Approximate Costs: Gaseous Chlorine and $Ca(OCl)_2$ Technology (Potable water, 1.2 MGD, 1 ppm chlorine dose)

	Cl_2 with scrubbers 150# cylinders	Cl_2 without scrubbers 150# cylinders	$Ca(OCl)_2$
Capital	$65,000	$15,000	$2,500
Operating	3,600	3,600	10,000
Maintenance	2,600	2,600	4,600

Sources: Matheson Gas Products (Cl_2); Van Waters and Rogers ($Ca(OCl_2)$)

MIOX^{tm} has been:

- available for about five years
- installed at about 500 sites worldwide
- used for potable and wastewater treatment.

The mixed oxidant solution generated by this process provides a much stronger oxidant potential than any of the individual components alone and also a measurable residual of chlorine.

Alternative 3: MIOX^{tm} (mixed oxidant)

This technology has been available for about five years and is installed at about 500 sites worldwide, including the Department of Energy sites, Los Alamos National Laboratory for wastewater treatment and Idaho National Engineering Laboratory for potable water. The MIOX^{tm} process involves the generation of a mixed oxidant solution using a maintenance-free (i.e., no membrane) electrolytic cell and feed of only salt water. A separate reaction feeder unit exists for the salt. This technology is similar to on-site production of NaOCl with the difference that the anode solution (i.e., oxidants) and cathode solution (i.e., reductants) are separated. The MIOX^{tm} company analyses show that the oxidant solution includes chlorine dioxide, hypochlorous acid, ozone and hydrogen peroxide (and possibly other oxidizing compounds). These oxidants work synergistically to kill a broader range of microbes more effectively than chlorine technology. [Additional information can be found at www.miox.com].

Advantages:

Since the technology uses only salt (NaCl) and water as feed to generate oxidants on-site, no toxic chemicals are handled or transported, thus reducing process safety compliance requirements. The mixed oxidant solution generated by this process provides a much stronger oxidizing potential than any of the individual components alone. Consequently, its general bacterial disinfection performance is faster than chlorine gas disinfection (2-5 times) and similar to ozone and chlorine dioxide. MIOX^{tm} is highly effective against *Giardia Excystation*, producing 99.99% inactivation after 30 minutes [www.miox.com] and effective against *Cryptosporidium parvum* oocysts, producing >99.9% inactivation in four hours with a 5 mg/liter concentration of mixed oxidants [Venczel et al., 1997]. A recent, yet unpublished study by M.D. Sobsey at the

University of North Carolina shows 94% inactivation in 30 minutes at a 4 mg/l oxidant concentration. In conjunction with the filtration pretreatment that is typical of most drinking water systems, this performance is estimated to be sufficient for elimination of *Cryptosporidium*.

The MIOX^{tm} technology also provides a measurable residual of chlorine, as required for secondary treatment throughout the distribution system. As an added benefit, the MIOX^{tm} process results in THM levels 20-50% lower than those produced by treatment with chlorine gas.

The MIOX^{tm} technology includes a chlorination-based disinfection strategy that leaves residual chlorine in the water and also produces disinfection by-products.

Disadvantages:

The MIOX^{tm} technology includes a chlorination-based disinfection strategy that leaves residual chlorine in the water, which may need removal prior to wastewater discharge into receiving streams. The process also produces disinfection by-products, which, though significantly reduced compared to chlorine gas, may require attention as the increasingly stringent regulations scheduled for the future are implemented.

Costs:

Capital costs for this system are approximately the same as chlorine gas systems. However, if scrubbers are necessary to control accidental leaks in the chlorine gas system, the capital costs of the mixed oxidant system are much lower, as shown in Table 4. The operating and maintenance costs of the mixed oxidant system are lower than those for gaseous chlorine. In addition, the MIOX^{tm} technology eliminates the costs associated with safety equipment and special training needed with gaseous chlorine systems.

Table 4. Approximate Costs: Gaseous Chlorine and MIOX^{tm} Technology
(Potable water, 1.2 MGD, 1 ppm chlorine dose)

	Cl_2 with scrubbers 150# cylinders	Cl_2 without scrubbers 150# cylinders	MIOX^{tm}
Capital	$65,000	$15,000	$21,000
Operating	3,600	3,600	2,200
Maintenance	2,600	2,600	1,300[a]

Sources: Matheson Gas Products (Cl_2); MIOX^{tm} Company, Albuquerque, NM

[a] Maintenance is generally cheaper than on-site NaOCl, since these cells do not require acid washing

The use of chlorine dioxide for pre-disinfection and oxidation of drinking water:

- has increased significantly over the past 20 years
- is generally not considered a competitive technology for wastewater disinfection.

Alternative 4: Chlorine Dioxide (ClO_2)

The use of chlorine dioxide for pre-disinfection and oxidation of drinking water has increased significantly over the past 20 years. Chlorine dioxide is currently used in about 13% of the drinking water treatment facilities in the US [USEPA, draft, 1998]. However, it is generally not considered a competitive technology for wastewater disinfection since it offers no significant technological advantage compared to chlorine, because additional salts (i.e., sodium thiosulfate) need to be added to the water. [WEF. *Wastewater Disinfection, 1996*].

Chlorine dioxide is a more efficient disinfectant than chlorine gas and reduces the production of THM by-products by oxidizing THM precursors [WEF *Wastewater Disinfection*, 1996]. It must be generated on-site because it is an unstable compound. Chlorine dioxide is an unstable gas that is explosive in air at concentrations above 10% by volume (this corresponds to 12gal/ l. in solution). It is always generated on-site in an aqueous solution and is used shortly after. These solutions can be stored up to seven days. Care must be taken to keep it in solution. Chlorine dioxide decomposes in sunlight.

The conventional chlorine dioxide generation process uses chlorine gas as feed to generate chlorine dioxide through the following reaction:

$$NaClO_2 + 1/2\ Cl_2 \rightarrow ClO_2 + NaCl.$$

However, other processes are available that do not use chlorine gas. For example, chlorite based generators [www.capitalcontrols.com/cat006.htm] use hypochlorite, hydrochloric acid, and sodium chlorite to produce chlorine dioxide through the following chemical reaction:

$$2\ NaClO_2 + HOCl + HCl \rightarrow 2\ ClO_2 + H_2O + 2\ NaCl$$

Another chlorine dioxide system, which is very new to the market [www.clo2.com/ecf/ecf2.html], employs an electrolytic cell, a gas pore membrane, and recirculation to produce pure chlorine dioxide from an aqueous solution of sodium chlorite. This new system has the advantage of having a single chemical feed and uses membrane separation to prevent any excess sodium chlorite and sodium chlorate (formed via side reactions) from contacting the resulting disinfected water. The chemical reaction involved in this process is:

$$NaClO_2 + H_2O \rightarrow ClO_2 + NaOH + \frac{1}{2}\ H_2.$$

Advantages:

Disinfection with chlorine dioxide produces much lower levels of THMs than chlorine gas and does not produce halogenated organic disinfection by-products at levels of concern (USEPA. DBP Stage 2 Rule, draft, 1997). Chlorine dioxide is a more effective disinfectant than chlorine, but is not as strong an oxidant as free chlorine (USEPA, No. 625489023, 1990). The newer systems mentioned above do not require chlorine gas transport or handling. The ECF-Sterling system has the additional advantages of being a single feed process that prevents chlorite or chlorate discharge.

Chlorine dioxide is a more effective disinfectant than chlorine, but is not as strong an oxidant as free chlorine.

Disadvantages:

With the conventional method, chlorine dioxide is generated on-site from sodium chlorite and chlorine gas, and thus requires all of the precautions associated with the transportation and handling of chlorine gas. In addition, since chlorine dioxide gas is explosive at levels above 10% in air [USEPA, draft 1998] special state safety regulations may apply. Chlorine dioxide production using chlorine gas or acid and hypochlorite generally requires an excess of chlorine or acid to maximize sodium chlorite conversion. If not controlled carefully, this can lead to untreated chlorite or excessive amounts of chlorine in the treated water. It can also lead to the formation of chlorate or chlorinated disinfection byproducts. The proposed Stage 1 Disinfectant By-Product Rule for chlorite sets a maximum contaminant level of 1.0 mg/l (combined chlorite and chlorate ions, and chlorine dioxide), which will likely be reduced in the Stage 2 rules. Thus, chlorine dioxide's use as a primary disinfectant may be limited in the future, except for very clean waters and/or short distribution systems that need only a small amount of disinfectant. (The new ECF-Sterling system, discussed earlier, apparently does not allow chlorite or chlorate to enter the treated water and therefore would not have this potential limitation). Chlorine dioxide has had taste and odor complaints, which have limited its use as a residual disinfectant.

> On-site generation of chlorine dioxide requires all of the precautions associated with the transportation in handling of chlorine gas, including possible application of special state safety requirements related to its explosive potential.

Costs:

Special operation, maintenance, and monitoring requirements may exist for systems using chlorine dioxide, depending on the state, which can significantly affect labor costs [USEPA. draft, 1998]. As shown in Table 5, the capital costs of ClO_2 systems are higher than those of chlorine gas systems that do not require scrubbers, but lower than those that do. The operating costs of ClO_2 systems are substantially higher than comparable chlorine gas systems. Maintenance costs are generally comparable.

Table 5. Approximate Costs: Gaseous Chlorine and ClO_2 Technology (Potable water, 1.2 MGD, 1 ppm chlorine dose)

	Cl_2 with scrubbers 150# cylinders	Cl_2 without scrubbers 150# cylinders	ClO_2 [a]
Capital	$65,000	$15,000	$30,000
Operating	3,600	3,600	10,000
Maintenance	2,600	2,600	2,500[a]

Sources: Matheson Gas Products (Cl_2); Vulcan Chemicals (ClO_2)

[a] For system using only NaOCl, $NaClO_2$, and HCl. This company provided estimates for current capital costs for their systems, however they provide a package that includes leasing and maintenance of their systems.

Chloramination:

- has been used to disinfect drinking water since the 1930s
- is now used mostly as a secondary disinfectant.

Chloramine is not as strong a disinfectant as chlorine, but is more stable, and thus provides longer lasting residual disinfectant.

Alternative 5: Chloramination

Chloramination, typically employing monochloramine (NH_2Cl), has been used to disinfect drinking water since the 1930s. It is currently used for disinfection in about 20 percent of the public water supply systems in the U.S. Because chloramines are more stable and last longer in water than chlorine, monochloramine is now used mostly as a secondary disinfectant because it provides more effective residual disinfection in the distribution system than chlorination alone. It is used especially where disinfection by-product formation in the distribution system is exceedingly high if free chlorine is used as the secondary disinfectant. Monochloramine may be produced on-site from ammonia and chlorine, or a preformed solution of monochloramine may be used. Monochloramine is generated on-site by either adding ammonia to water containing chlorine or adding chlorine (gas or hypochlorite) to water containing ammonia.

Advantages:

Chloramine is not as strong a disinfectant as chlorine but is more stable, and thus provides longer lasting residual disinfectant, an advantage for distribution systems. Due to its relatively low oxidation potential, chloramination does not form disinfection by-products at levels of concern [USEPA, Office of Water, draft 1997]. However, the EPA has expressed an interest in investigating the type and quantity of disinfection by-products that are produced by interactions between chloramines, bromide, brominated organics, and by the chloramination of ozonated waters [USEPA, Office of Water, draft 1997]. EPA's findings may influence chloramine's use in the future.

Disadvantages:

On-site generation of monochloramine requires chlorine gas or hypochlorite, which means that the safety precautions associated with chlorine gas or liquid hypochlorite apply. In addition, safety provisions are required to prevent the formation of nitrogen trichloride and the vaporization of ammonia at ambient temperatures [USEPA, draft, 1998]. Because monochloramine is a weak disinfectant, especially against cysts and viruses, the contact times required for adequate primary disinfection are much longer and higher than with chlorine (or other alternatives). Therefore, chloramines are not generally chosen for primary disinfection.

On-site generation of monochloramine requires chlorine gas or hypochlorite, (with associated safety requirements). Chloramines are generally not chosen for primary disinfection.

Costs:

Since chloramines are not generally used for primary disinfection, system costs have not been estimated for this technology. Systems using chloramines are adding a second chemical and an additional injection system, thus adding an increment to all three components of cost (capital, operation, and maintenance).

Alternative 6: Ozone (O_3)

Ozone:

- has been used for potable water treatment for nearly a century
- is used more frequently in large potable water treatment systems than in small or medium-sized systems
- has been used increasingly for potable water treatment as compared to wastewater treatment.

Ozone is always generated on-site.

Ozone technology has been used for potable water treatment for nearly a century, since the first plant was built in Nice, France. Western Europe has long relied extensively on ozone technology [Lamarre, 1997]. A number of drinking water treatment plants in the United States have recently switched to ozone in response to increasingly stringent water quality standards. Ozone is sometimes combined with hydrogen peroxide or ultraviolet light to enhance oxidizing performance and applied in a multipurpose effort to achieve primary disinfection, destroy algae-derived tastes and odors, and minimize byproduct formation upon secondary disinfection with chlorine-based technologies.

In 1997, the International Ozone Association surveyed 158 U.S. water treatment facilities using ozone and found that about 40% of them were using the ozone for disinfection purposes, rather than for odor or taste control purposes. In the U.S., ozone is used more frequently in large potable water treatment systems than in small or medium-sized systems. [USEPA draft 1998].

The use of ozone for wastewater disinfection has not increased at a rate comparable to its use in drinking water disinfection, probably due to its high costs and early design failures with several plants [EPRI, CR-106435, 1996]. However, given the direction of chlorine discharge regulations, future use of this technology may accelerate.

Ozone, which is a very powerful oxidant, is always generated on-site. It is extremely unstable and cannot be stored for any length of time. Ozone (O_3) is generated by applying high voltage electricity across a gap (tube) through which filtered dry air or pure oxygen is passed (corona discharge method). The high energy current causes oxygen to recombine to ozone through the following reaction:

$$3O_2 \rightarrow 2O_3$$

Ozone disinfects by oxidizing the cell walls of microorganisms, which then disintegrate (lyse), destroying the microorganism. This is a very different mechanism than with chlorine, which diffuses through the cell wall, making the cell susceptible to enzymatic attack [Nebel, 1981]. For this reason, ozone disinfects much faster than chlorine, killing *E. coli*, for example, approximately 3000 times faster than chlorine.

Ozone offers a number of significant advantages over chlorine gas and other chlorine-based disinfection alternatives.

Ozone generators can be scaled to treat a wide range of water flow rates. For example, one manufacturer of ozone systems (OREC) can provide generators that produce ozone at rates ranging from grams/hour to 50 kilograms/hour. Because multiple generators can operate in parallel, there is essentially no technical limit to the incoming water flow rate that could be treated. Although the operation of the ozone systems requires only modest skill levels and time, maintenance of the generators, which consists primarily of overhauling air separators, oxygen concentrators, and ozone generators every few years, requires highly skilled technicians.

Advantages:

Ozone offers a number of significant advantages over chlorine gas and other chlorine-based disinfection alternatives. First, because ozone is always generated on-site, it does not require transportation or storage of dangerous materials. Second, ozone is highly efficient for killing bacteria, viruses, and protozoa (e.g., *Giardia lamblia* and *Cryptosporidium*). For example, the Ct value (dose in mg/l x time in minutes) required for the inactivation of *Giardia* cysts is about 100 times greater for free chlorine

Advantages of ozone include:

- on-site generation
- high efficiency in killing pathogens
- dechlorination not required
- high reliability.

than for ozone; for viruses it is six times greater. Ozone is the only recommended primary disinfectant for *Cryptosporidium*.

Third, as it disinfects, ozone also oxidizes inorganic and organic impurities such as iron and manganese, and will also oxidize sulfides. This assists in filtration. Because it is a 50 percent stronger oxidizer than chlorine, ozone requires significantly less contact time to remove inorganic/organic compounds than conventional methods.

A fourth major advantage is that ozone does not produce the THM disinfection by-products that result from chlorine disinfection, although if bromine is present in the water, bromate will be formed, which has a Stage 1 maximum concentration level of 0.010 mg/l. A fifth advantage is that wastewaters treated with ozone do not contain chlorine or chlorinated disinfection byproducts, thereby making dechlorination unnecessary. In addition, ozone treatment increases dissolved oxygen levels in wastewater, eliminating the need for effluent reaeration. An added advantage for wastewater treatment plants already having oxygen activated sludge processing is that the off-gas oxygen from the ozone process can be recycled directly into the activated sludge reactor, resulting in no loss of O_2.

A final advantage is that, although ozone systems are relatively complex, they are highly automated and very reliable [USEPA draft 1998].

Because of its toxicity, ozone needs to be consistently monitored.

Disadvantages:

Ozone also has some disadvantages as a disinfection technology, most deriving from its toxic nature. Because of its toxicity, ozone needs to be consistently monitored. In an ozone system, the chamber in which the ozone is bubbled up through the water, known as the contactor, emits off-gas that usually contains higher than fatal concentrations of ozone [USEPA draft 1998]. For this reason, ozone systems are designed to collect the off-gas and send it to a destruct unit heater where it is converted back to oxygen prior to release to the atmosphere. These destruct units are designed to reduce the concentration of ozone in the released gas to 0.1 ppm, which meets the OSHA standard for exposure in an eight hour shift [USEPA draft 1998]. To ensure safety, ozone detectors must be installed in spaces where ozone gas and personnel are routinely present as well as at the outlet from the off-gas destruct unit, and linked to procedures that ensure shut-down if a gas leak should occur. A related disadvantage is the need to ensure conformance with building regulations and fire codes concerning the storage of liquid, high-purity oxygen.

Ozone has a very short half-life and does not provide a residual disinfectant.

Another disadvantage to the use of ozone in drinking water systems with extensive distribution networks is the need to add a residual or secondary disinfectant such as chlorine, chlorine dioxide, or chloramine to meet the EPA requirement of 0.2 ppm residual disinfectant. Ozone has a very short half-life -- about 20 minutes in air and water depending on pH and temperature. Consequently, ozone reverts back to oxygen and enters the atmosphere quite quickly, leaving essentially no residual disinfectant properties if used alone.

Costs:

Ozone has comparatively high capital costs, but relatively low operating and maintenance costs, as shown in Table 6. It is electricity intensive, and is not yet well understood by many designers and regulators in the United States. As a result, it is generally not considered to be cost competitive with chlorination/dechlorination and ultraviolet light technologies for wastewater treatment systems.

Table 6. Approximate Costs: Gaseous Chlorine and Ozone Technology (Potable water, 1.2 MGD, 1 ppm chlorine dose)

	Cl_2 with scrubbers 150# cylinders	Cl_2 without scrubbers 150# cylinders	O_3 [a]
Capital	$65,000	$15,000	$75,000
Operating	3,600	3,600	1,000
Maintenance	2,600	2,600	1,600[a]

Sources: Matheson Gas Products (Cl_2); Osmonics, Vancouver, WA (O_3)

[a] Does not include cost of residual chlorine source.

Ultraviolet light, a non-chemical alternative, is used primarily for wastewater treatment.

Ultraviolet light disinfection does not use chemical feeds or produce toxic by-products, thereby reducing the need for safety measures.

Alternative 7: Ultraviolet (UV) Light

Ultraviolet light is used primarily for wastewater treatment. Although the majority of facilities using this technology are located in Canada and Europe, ultraviolet light systems have gained considerable popularity for wastewater treatment in the United States during the past decade or so as a non-chemical alternative that eliminates the problems associated with chlorination/dechlorination. In an ultraviolet light system, water flows past ultraviolet lamps to expose microbes to energy at a germicidal wavelength of 253.7 nanometers. This exposure modifies the DNA in the cells of contaminants (bacteria, viruses, molds, algae, etc.) so that they can no longer reproduce, and thus present no threat to human health. In the United States, the EPA has approved ultraviolet light disinfection for drinking water only for systems unaffected by surface water sources [Naude, A.1997].

Advantages:

The principal advantages of ultraviolet light disinfection are that it does not use chemical feeds and does not produce toxic by-products. As a result, ultraviolet light systems do not need a dechlorination process and required safety measures are greatly reduced compared to systems using chlorine gas. An additional advantage is that ultraviolet light is more effective than chlorine in inactivating most viruses and spores [Darby et al., 1995] and ultraviolet systems require relatively short contact times to inactivate bacteria [WEF, Wastewater Disinfection, 1997].

Disadvantages:

The primary disadvantage of ultraviolet light for potable water disinfection is that it does not provide a disinfecting residual. It is therefore not suitable for significantly sized drinking water distribution

Ultraviolet light disinfection:

- does not provide a disinfecting residual
- is not suitable for significantly sized drinking water distribution systems without the addition of a secondary disinfectant such as chlorine.

systems without the addition of a secondary disinfectant such as chlorine, chlorine dioxide, or chloramine to meet the EPA required 0.2 ppm residual disinfectant. Ultraviolet light is also ineffective against *Giardia* cysts (WEF, *Wastewater Disinfection, 1997*). And is therefore not a good candidate for disinfecting water that is influenced by surface water sources. In addition, suspended and dissolved materials can impede the performance of ultraviolet light, thus requiring care, and potentially additional treatment, to ensure adequate visual clarity of the water as it passes by the lights. Because it provides no residual disinfectant and lacks an immediate measure of disinfection success (unlike chlorination systems), particular attention must also be paid to ensure that a lethal dose of ultraviolet light is being applied to organisms. Otherwise, re-infection of water can occur.

Costs:

Ultraviolet systems are relatively simple to operate and maintain. In addition, they often require less space than chlorine systems. [Darby et al, 1995]. Although the capital and maintenance costs of ultraviolet light systems are currently relatively expensive compared to chlorination systems, as shown in Table 7, costs are coming down as the technology is refined and improved.

Table 7. Approximate Costs: Gaseous Chlorine and Ultraviolet Light Technology (Potable water, 1.2 MGD, 1 ppm chlorine dose)

	Cl_2 with scrubbers 150# cylinders	Cl_2 without scrubbers 150# cylinders	UV [a]
Capital	$65,000	$15,000	$42,000
Operating	3,600	3,600	1,000
Maintenance	2,600	2,600	5,000[a]

Sources: Matheson Gas Products (Cl_2); Atlantic Ultraviolet Corp, Hauppauge, NY (UV)

[a] Does not include cost of residual chlorine source.

5. Comparisons Across Technologies

This section presents summary comparisons of performance and costs of the currently available technologies. Table 8 presents a matrix of performance measures for each technology. Table 9 presents approximate capital and operating costs for each alternative. Appendix A lists some facilities that have recently implemented these technologies and provides contact information for each of the technologies.

Performance Comparisons

Table 8 summarizes and highlights how the seven currently available alternatives examined in this study compare to gaseous chlorine in terms of:

- disinfection capability (bactericidal, virucidal, cysticidal)
- generation of hazardous disinfection by-products
- persistent residual
- safety concerns
- complexity of operations and maintenance
- size applicability
- relative cost
- long term applicability for potable and wastewater systems.

Table 8. Performance of Disinfection Technologies on Key Characteristics

Attributes	Baseline	Alt. 1	Alt. 2	Alt. 3	Alt. 4	Alt. 5	Alt. 6	Alt.7
	Cl_2	**NaOCl/ On-site- NaOCl**	**$Ca(OCl)_2$**	**MIOX™**	**ClO_2**	**Chloramines**	**O_3**	**UV**
Disinfection Capability:[1] Bacteria	Good	Good	Good	Good	Good	Poor	Very Good	Very Good
Viruses	Poor	Poor	Poor	Good	Good	Poor	Very Good	Fair
Cysts	Poor	Poor	Poor	Fair[1]	Fair[1]	Poor	Good	No effect
Generation of Hazardous Disinfection by products	Yes - THMs And HAA5	Yes- THMs and HAA5	Yes- THMs and HAA5	Yes, but less THMs than Cl_2	Yes, but less THMs than Cl_2 Chlorite/ chlorate produced	Yes, but less THMs than Cl_2	Yes, Bromine Insig. Levels THMs formed	None
Persistent Residual	Good	Good	Good	Good- (longer than Cl^2)	Fair	Very Good	None (good for ww)	None (good for ww)
Safety Concerns	High	Low (for on-site)-Medium	Low	Low	Medium-High[2]	Medium	Medium	Low
Complexity of Operations/ Maintenance)	Minimal	Minimal	Moderate[3]	Moderate	Moderate	Minimal	Moderate	Minimal
Size Applicability	All sizes	All sizes	Small-medium (cost)	All sizes	Small-medium	All sizes	Medium-large	Small-medium
Relative Cost	Low	Low	Moderate	Low	Moderate	Low	High	Moderate
Long Term Applicability For:[5] Potable Water	Low (safety issues)	Medium	Medium	Medium	Medium	Effective only for residual purposes	Medium-must have residual	Medium-must have residual
Waste-water	Medium	Medium	Medium	Medium	Low (cost)	None	High	High

1. Still may require filtration prior to discharge of wastewater.
2. Depending on the method used to generate chlorine dioxide, safety concerns can range from high to moderate.
3. Handling of Ca(OCl)2 is generally more labor-intensive than liquid (i.e. NaOCl)
4. From USEPA Wastewater Disinfection Manual (1986) and communication with equipment manufacturers/vendors.
5. Ability to meet upcoming standards.

Cost Estimates for Alternative Disinfection Technologies

To help FORSCOM staff with the evaluation of the seven alternatives, operating and capital costs were estimated for chlorine gas and each alternative disinfection technology, as summarized in Table 9, below. It is important to note that these estimates were not derived from a detailed cost analysis. Consequently they are intended only to provide order-of-magnitude information. A plant capacity of 1.2 million gallons per day (MGD) potable water treated operating for 24 hours per day, at a chlorine dose of 1 ppm (or, for alternatives, a dose that would produce comparable disinfection results) was assumed for the estimates. The price of electricity was assumed to be $0.042 per kilowatt hour (average for Washington State). Use of chlorine-based disinfection systems for waste water treatment are assumed to cost more due to the need for dechlorination prior to discharge. Other assumptions are listed as notes to Table 9.

Table 9. Approximate Costs for Alternative Disinfection Technologies (1.2 MGD, 1 ppm chlorine dose)

	Cl_2[1]	**Cl_2[2]**	**NaOCl[3]**	**On-site NaOCl[4]**	**Ca $(OCl)_2$[3]**	**MIOX[tm 5]**	**ClO_2[7]**	**O_3[8]**	**UV[9]**
Capital	65,000	15,000	2,500	18,000	2,500	21,000	30,000	75,000	42,000
Operating	3,600	3,600	4,400	1,500	10,000	2,200	10,000	1,000	1,000
Maintenance	2,600	2,600	5,000	1,600	4,600	1,300[6]	2,500	1,600	5,000

1. 150# cylinder with scrubbers – prices from Matheson Gas Products.
2. 150# cylinder without scrubbers – prices from Matheson Gas Products.
3. Prices from Van Waters and Rogers.
4. Prices from TMG Services, Maple Valley, WA.
5. Prices from MIOX[tm] Company, Albuquerque, NM.
6. Maintenance is generally cheaper than on-site NaOCl, since these cells do not require acid washing.

7. Prices from Vulcan Chemicals, for a system using only NaOCl, NaClO2, and HCl. This company provided estimates for current capital costs for their systems, however they provide package which includes leasing and maintenance service of their systems.
8. Prices from Osmonics, Vancouver, WA. (Does not include cost of residual chlorine source)
9. Prices from Atlantic Ultraviolet Corp., Hauppauge, NY. (Does not include cost of residual chlorine source)

6. Summary

To make decisions on alternative technologies, FORSCOM will need to make cost trade-off decisions. For example, when looking at the attribute "capital cost", ozone is the most expensive alternative of all the technologies listed in this report. It also requires additional monitoring (need to convert ozone to oxygen) to eliminate a potential hazard. However, ozone is also the best disinfectant and does not produce a hazardous by-product. This report will assist decision makers in understanding trade-offs associated with selecting one alternative technology over another. Given the dedication of FORSCOM to the safety and well-being of its personnel as part of the decisionmaking process it will also be important to consider the cost [i.e., personnel, documentation] of safety compliance.

Some of the highlights of this report are:

- All of the disinfection technologies discussed in this paper are currently available for primary disinfection of potable water and wastewater, and are scalable to virtually any size system, either by the use of different sized units or combinations of standard units. While system designs tend to be standardized, some level of engineering will usually be required to integrate any of these technologies into existing water treatments systems.

- Chlorine-based technologies can provide quick and simple replacements for gaseous chlorination systems. On-site generation of sodium hypochlorite and mixed oxidants from a brine solution eliminate both public and worker exposures to toxic chemicals.

However, on-site generation of sodium hypochlorite produces hydrogen, which presents a fire or explosion hazard if not properly vented. An advantage of the mixed oxidant technology is that it produces fewer disinfection byproducts than gaseous chlorine, which can be important for installations whose current disinfection byproduct levels will not meet the more stringent EPA standards.

- The non-chlorine-based technologies (ozone and ultraviolet light) have relatively high capital costs. Because ozone is a toxic chemical, ozone systems require monitoring and the ability to convert ozone to oxygen in case of a leak. Consequently, ozone systems have the highest capital costs of the alternatives considered, and do not eliminate potential hazardous exposures of workers. However, ozone provides the best disinfection capability of the alternatives examined. Both ozone and UV technologies have an advantage for wastewater applications because they disinfect without requiring dechlorination prior to discharge. Neither ozone nor UV produces hazardous disinfectant by-products. However, if either of these technologies are used to disinfect drinking water, chlorine or a chlorine-based alternative must be used to provide the residual, or secondary, disinfection capability needed in the water distribution system. In addition, UV is not approved as a treatment for surface water sources that may contain hazardous cysts.

- As mentioned in the beginning of this report, the cost of equipment and products used in waste water systems is highly influenced by state and regional variability, and the characteristics, and quality and volume of the water. Accurate cost estimates can therefore only be developed on a site-specific basis.

Further Reading

1. "Ozone Reference Guide: An Overview of Ozone Fundamentals and Municipal and Industrial Ozone Applications," CR-106435, prepared by Electric Power Research Institute Community Environmental Center, April 1996.

2. "Alternative Disinfectants and Oxidants Guidance Manual," EPA Contract No. 68-C6-0059, draft report, to be published Nov. 1998.

3. "Wastewater Disinfection Manual of Practice," Water Environment Federation, Manual of Practice FD-10, 1996

References

Darby, J., Heath, M., Jacangalo, J., Loge, F., Swaim, P. and Tchobanoglous, G. "Comparison of UV Irradiation to Chlorination: Guidance for Achieving Optimal UV Performance (Disinfection)," final report prepared for Water Environment Research Foundation, Project 91-WWD-1, 1995, p.44.

Electric Power Research Institute (EPRI) Community Environmental Center. *Ozone Reference Guide: An Overview of Ozone Fundamentals and Municipal and Industrial Ozone Applications*. CR-106435, April 1996, p. VIII25.

Lamarre, Leslie. "A Fresh Look at Ozone," EPRI Journal, July/Aug 1997, pp.6-15.

Naude, Alice, "Finding Choices In Disinfection," Chemical Marketing Reporter, October. 13, 1997. (off of internet site, www.clo2.com/reading/waternews/choice.html)

Nebel, Carl. "Ozone Treatment of Potable Water- Part 1," Public Works Journal, June 1981, p.86.

USEPA, Office of Water, DBP Stage 2 Rule and Long-Term 2 Enhanced Surface Water Treatment Rule: Draft Report on Research to Support Rules, Nov. 12, 1997, prepared for Nov. 19th, 1997, M/DBP Stakeholder meeting.

USEPA. *Technologies for Upgrading Existing or Designing New Drinking Water Treatment Facilities*, EPA /6254-89/023, March 1990.

USEPA. *Design Manual: Municipal Wastewater Disinfection*, EPA/625/1-86/021, October, 1986.

USEPA. *Alternative Disinfectants and Oxidants Guidance Manual*. HDR Engineering, Inc. Contract No. 68-C6-0059, draft report, to be published Nov. 1998. P.14.

Venczel, Linda V., Arrowood, Michael, Hurd, Margaret, and Sobsey, Mark D., "Inactivation of *Cryptosporidium parvum* oocysts and *Clostridium perfringens* Spores by a Mixed-Oxidant Disinfectant and by Free Chlorine," Applied and Environmental Microbiology, Apr. 1997, p. 1598-1601.]

Water Environment Federation (WEF*). Wastewater Disinfection Manual of Practice*, Manual of Practice FD-10, 1996.

APPENDIX A.

Demonstrated Applicability of Alternative Disinfection Technologies and Contacts for Technologies

Sodium Hypochlorite (NaOCl)

1. Fort Lewis – drinking water facility. Recent studies at this plant (performed by Gray and Osbourne Company) have resulted in a reduced NaOCl usage. More specifically, they have found that with using NaOCl, they can significantly reduce the dose of chlorine necessary (they use equal pounds of NaOCl as they would of Cl_2 gas) without sacrificing disinfection performance (coliform count and residual).

2. DOE – Savannah River Site converted to sodium hypochlorite systems to replace gaseous chlorination several years ago.

On-Site NaOCl

No demonstration sites

Manufacturers: Capital Controls, US Filter, Chemical Services, MIOX^{tm}

Contact:

Ken Fletcher

TMG Services

Maple Valley, WA

425-432-4020

Calcium Hypochlorite (Ca(OCl)$_2$

1. Charles County Water District of LaPlata, Md., switched to using calcium hypochlorite system for treatment of drinking water (wells) to serve about 600 people (25,000-50,000 gallons/day) and are very happy with the system performance. For more info, contact Michelle Cutler, Operations Superintendent, Charles County Water District, (301) 609-7403.

2. Campbellsville, Kentucky uses calcium hypochlorite to treat 4 million gallons per day of drinking water to serve 15,000 people in a 20 sq mi radius. They switched to this system from chlorine gas because it

provides a safer means of disinfecting than chlorine gas and also gives longer lasting residual to the outer limits of the service area.

3. Metropolitan Western Water Improvement District, Tucson, AZ has been using calcium hypochlorite (PPG Industries) since 1994 to serve 45,000 people. For more info, contact Larry Tanner, Production Supervisor, Metropolitan Wester Water Improvement District, (520) 575-8100.

Manufacturers: Capital Controls, US Filter, Chemical Services, MIOX^{tm}

Contact:

PPG

Shayne Gargala

1-800-245-2974

MIOX^{tm}* -- *Potable Water

1. Johnston Atoll in the South Pacific - potable water (administered by Hickam AFB in Hawaii) White Sands Missile Range in N.M. - potable water (Holloman AFB)

2. Idaho National Engineering Labs in Idaho - potable water (TRA site) for more information contact: Dave Rousel at (208) 533-4477

3. Idaho National Engineering Labs in Idaho - potable water (PBF site)- for more information contact: Rick Gavalya at (208) 526-6612.

4. Bureau of Reclamation in CA - potable water (Tracy Project)

5.Osan AFB in Korea - potable water

6.Cordoba, Mexico, at an EPA / USDA site for potable water

7.Several sites for the Bureau of Indian Affairs (BIA).

8.A request for basewide installation of this technology has been made at Kirtland AFB – this would be a total 7 MGD capacity for potable water if the request goes through.

MIOX^{tm} -- Wastewater

Los Alamos National Laboratories in N.M. - waste water (TA-46 site treats about 3 MGD) - The SWSC Wastewater plant at Los Alamos National Lab has estimated that they are saving $10,000/year in safety-related costs by replacing chlorine gas with MIOX^{tm}. For more information, contact: Ed Hoth at (505) 665-6002.

contact:

Manufacturers: MIOX^{tm} Corporation

Contact:

Katie Bolek

Marketing & Materials

MIOX^{tm} Corporation

5500 Midway Park Pl. NE

Albuquerque, NM 87109

Ph: (505) 343-0090, x26

FAX: (505) 343-0093

Toll-Free: (888) 646-9426

Chlorine Dioxide (ClO_2)

1. Fort Benning, Columbus, GA. They have been treating drinking water with this method for approximately 6 years.
2. Laval, Quebec- This city has been using this a CIFEC generator since 1984 for potable water treatment.

Manufacturers: Vulcan Chemicals; Biocide International;
Bailey, Fischer and Porter

Contact:

Maurice Gutierrez

Vulcan Chemicals

916-375-2368

Rob Danner

Biocide International

405-329-5556

Bruce Loller

Bailey, Fischer and Porter

215-674-6772

Chloramination

1. The East Bay Municipal Utility District serving the San Francisco Bay area has recently switched to from chlorination to chloramination to disinfect its drinking water (www.epa.gov/region09/water/chloramine.html).

Ozone (O_3)

1. Metropolitan Water District of Southern California, Los Angeles. – They are using ozone in combination with hydrogen peroxide to achieve simultaneous disinfection and taste/odor control in their drinking water treatment operations. The technology has been extensively tested and proven cost-effective by the District. Two plants of capacities 750 million gallons per day (will be the largest potable water plant using ozone in the world) and 350 million gallons per day will be on-line during 1998.

Manufacturers: Osmonics Corporation; Tempest Environmental Systems; EDC Ozone Systems

Contacts:

Mike Lethola

Osmonics Corporation

360-891-6670

Tempest Environmental Systems

919-688-1460

Ultraviolet (UV)

1. The wastewater treatment facility in Olympia, WA has been using UV disinfection for approximately 6 years. They are getting a coliform count of 2-3 with this method.

Manufacturers: Atlantic UV Corp; Capital Controls; American Ultraviolet Company

Contacts:

Arlene

Atlantic UV Corp

516-273-0500

Capital Controls

215-997-4000

American Ultraviolet Company

714-834-1331